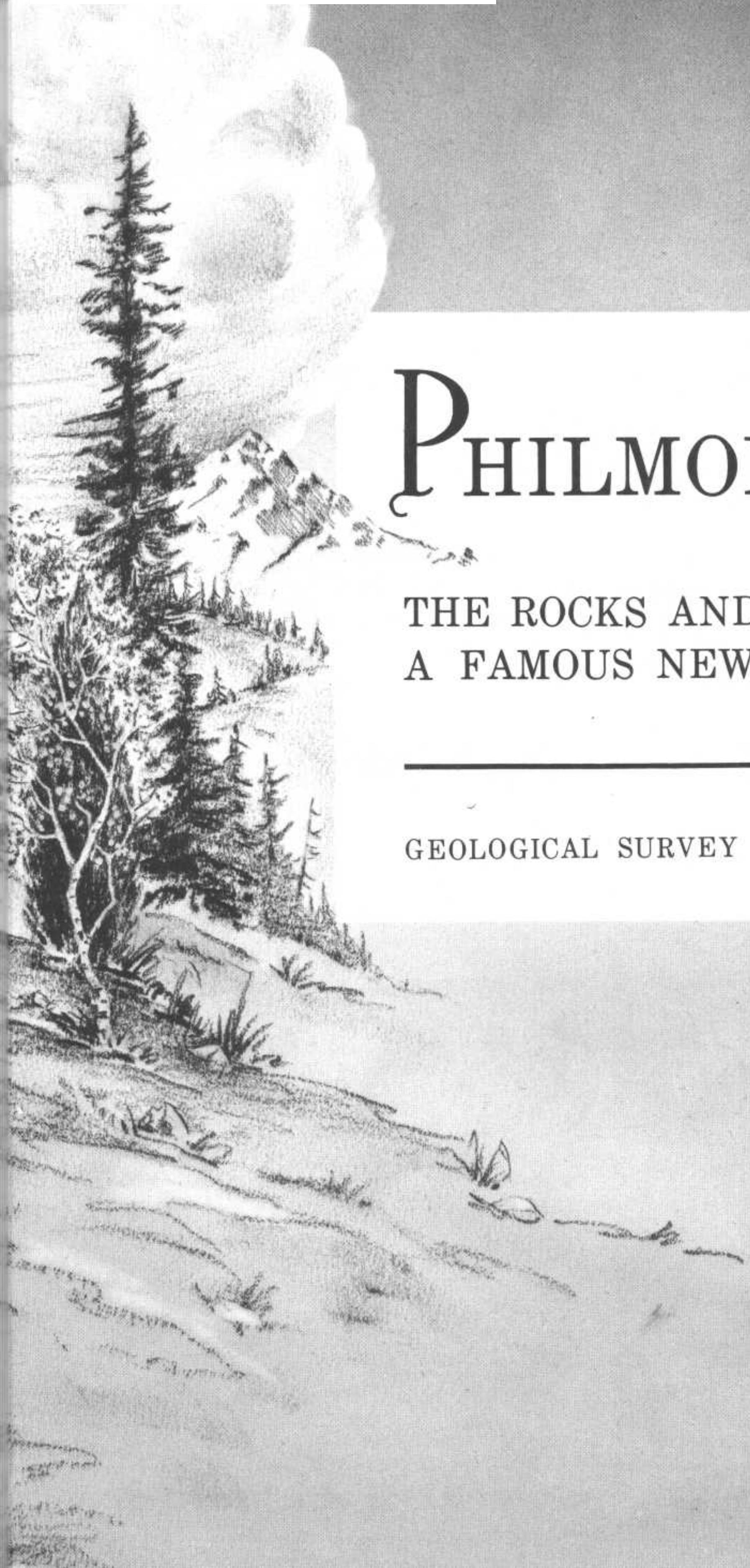

PHILMONT COUNTRY

THE ROCKS AND LANDSCAPE OF A FAMOUS NEW MEXICO RANCH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 505

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THE ROCKS AND LANDSCAPE OF A FAMOUS NEW MEXICO RANCH

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by
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GEOLOGICAL SURVEY PROFESSIONAL PAPER 505

The geologic story of the last billion eventful years in the Philmont Ranch region, where the Cimarron Range rises from the High Plains

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Thomas B. Nolan, *Director*

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FOREWORD

This book is an informal account of the geology of the Philmont Ranch quadrangle, where the Southern Rocky Mountains meet the Great Plains in northeastern New Mexico.

From time to time the U.S. Geological Survey publishes nontechnical accounts of the geology of places visited by large numbers of people, such as the National Parks and Monuments. The Philmont Ranch quadrangle is such a place. Its stirring scenery and romantic past attract many thousands of visitors each year, and thousands more discover it as they travel to better-known Taos and Santa Fe on U.S. Highway 64. Moreover, half the quadrangle is occupied by the Philmont Scout Ranch, which is visited by several thousand adults annually for training in Scout leadership, and by many thousands of Explorer Scouts each summer for protracted camping expeditions. The quadrangle is part of a region that, because of its known and potential mineral wealth, has been under investigation by the Geological Survey for many years. Some of the technical data thus assembled are here recast in a form that we hope will be of interest and use to those who visit the area.

Thomas B. Nolan

THOMAS B. NOLAN
Director, U.S. Geological Survey

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[Plates are in pocket]

FIGURES

[Photographs of rocks and fossils from beyond Philmont are indicated by *]

WHAT THIS BOOK IS ABOUT

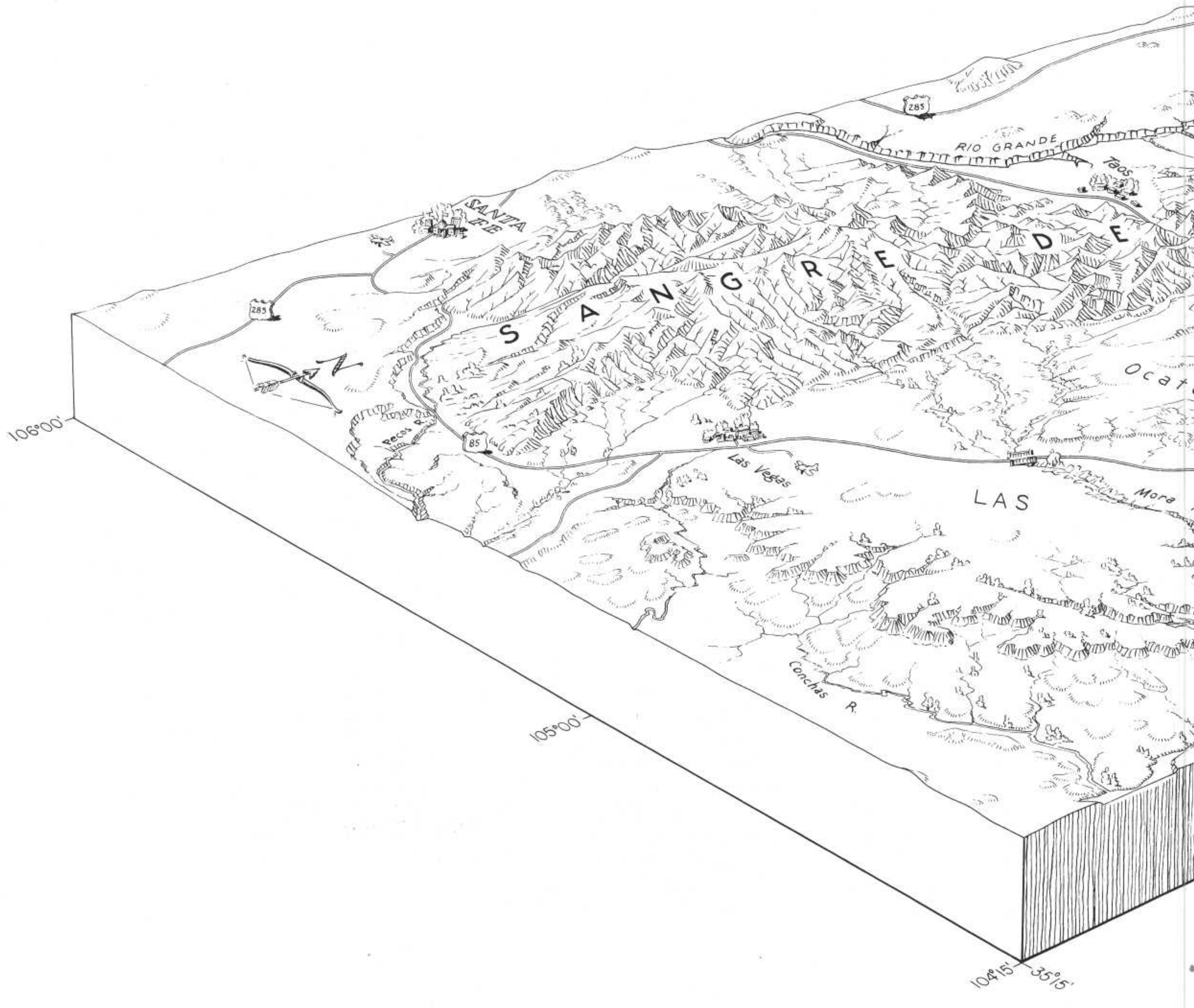
The geologic story of the Philmont Ranch region is mostly the story of one of the mountain ranges that make up the Rocky Mountains—the Cimarron Range in northeastern New Mexico. In a way it is an autobiography, for the range tells its own story, but in a difficult tongue. We are simply the translators. It is no epitaph, for the range is still young. The story is long, for some of the rocks in the core of the range are among the oldest on the North American continent, and those on the flanks of the range are still forming today. It is an incomplete story, but the missing events whet our curiosity. Parts of the rocky record can be read in more than one way, and this adds spice to the telling.

How the range got its name has been forgotten. Most likely it was named by Spanish explorers, who were the first Europeans to see it. In 1540, Coronado came as far north as Taos, but not until a century or more later did the Spaniards venture this far north along the east front of the mountains, in search of precious metals and jewels, not in the ground but in legendary El Dorados, Cities of Gold. Here they found no golden cities, but they saw dark, timbered mountains swarming with mountain sheep, deer, elk, bear, puma, and smaller animals. The Spaniards, or their successors, began speaking of the mountains as the Sierra Cimarron, or Range of the Wild Beasts.

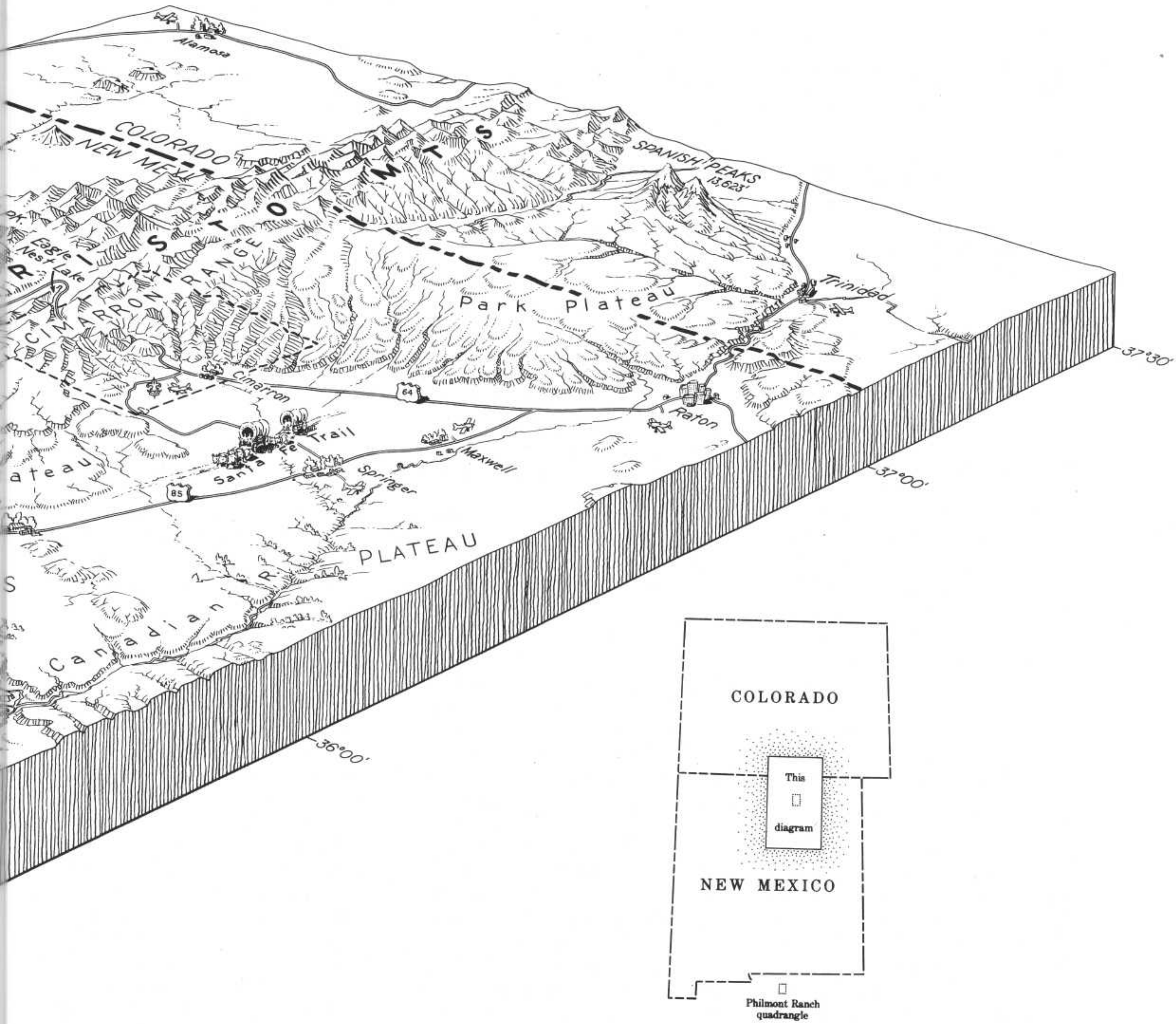
The name is no longer very apt, because the animal population has declined as the gun-toting population has grown. Mountain sheep became extinct decades ago, and descendants of the other large animals exist only under the protection of the law. The game that once ranged the bordering plains—buffalo, pronghorn, giant rabbit, and coyote—has almost vanished, too. On the other hand, animals unknown to the Indians until the Europeans came—horses, burros, cattle, and domestic sheep—are now many.

We are all aware of how rapidly the pattern of animal life has changed in the West. It is harder to realize that the mountains change too. But in the vast span of recorded geologic time—something like a billion years in this region—the Cimarron Range has existed but a brief 50 or 60 million years, and in its lifetime it has constantly, if slowly, changed. We hope to piece together, from evidence in the rocks and landscape, what happened before the mountains were born, how they came to be, and what has been happening to them since. Our account will be more a detective story than a lecture.

In working out the life story of the Cimarron Range and of the plains at its feet we will work backward. First, we will consider the landscape of today (fig. 1). Then we will examine the nature and origin of the rocks and water beneath this landscape—take, as it were, a geologic inventory. Third, we will work out the order in which the rocks of Philmont have formed, and when. After that we will find how and when the rocks have been deformed and changed by forces from within the earth. Next, we will try to decide how the landscape has been shaped. Finally, we will fit what we have seen of the rocks and scenery, and what we have reasoned about them, into a single, marvelously eventful, if incomplete, story—a geologic history.



WHERE THE ROCKIES RISE FROM THE PLAINS: the setting of the Philmont Ranch region. (Fig. 1)


Alamosa
COLORADO
NEW MEXI
SPANISH PEAKS
13,623'
Eagle Nest Lake
CIMARRON RANGE
Park Plateau
Trinidad
Cimarron
64
Raton
Santa Fe Trail
Maxwell
Springer
85
PLATEAU
Canadian
37°30'
37°00'
36°00'
COLORADO
This
diagram
NEW MEXICO
Philmont Ranch
quadrangle

A BIRD'S-EYE VIEW

The Philmont Ranch region—Philmont for short—covers 420 square miles of the area where the Rocky Mountains meet the Great Plains in northeastern New Mexico. Figure 1, on the preceding two pages, shows how a bird, flying high enough, would see the region. In the western part of Philmont rise the timbered peaks of the Cimarron Range, whose crests are 10,000 to 12,000 feet above sea level. To the north the range joins the still higher Sangre de Cristo Mountains, which extend for 200 miles along the Rocky Mountain front in southern Colorado and northern New Mexico. Separating most of the Cimarron Range from the main mass of the Sangre de Cristo Mountains is Moreno Valley. Along the west side of the mountains flows the Rio Grande. The famous Ranches of Taos are on the west flank of the mountains, as, farther south, is historic Santa Fe, capital city of New Mexico for more than 400 years and under four flags.

In the southeastern part of Philmont, the mountains rise suddenly from the gravel-clad plains of the Las Vegas Plateau, which

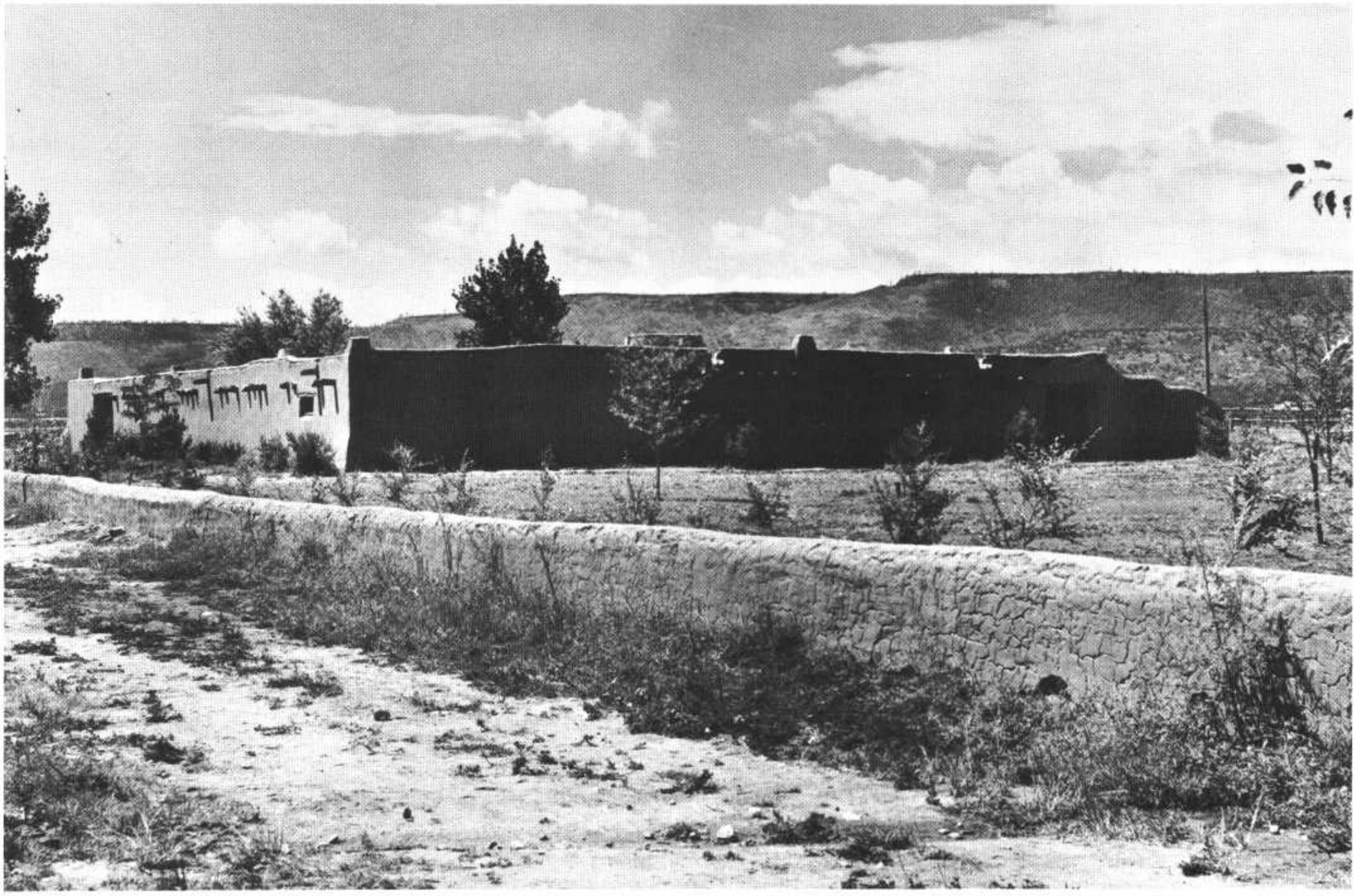
Oklahoma and Texas borders.

Elsewhere, a strip of steep-fronted rocky mesa lands separates the plains from the mountains. Mesas or benchlands in northern Philmont are part of the Park Plateau, a 40-mile-wide upland that rises 500 to 1,000 feet above the Las Vegas Plateau and extends 70 miles northward to the base of the Spanish Peaks, in Colorado. The coal-mining cities of Raton in New Mexico and Trinidad in Colorado are at the eastern edge of the Park Plateau. At the south end of Philmont, the Cimarron Range ends abruptly at lake-dotted mesa lands of the Ocaté Plateau, which stands 9,000 to 10,000 feet above the sea, or 2,000 to 3,000 feet above the plains. The Ocaté Plateau continues southward for 35 miles to the Mora River.

The storied Santa Fe Trail followed the western edge of the plains at the base of the benchlands. It swung southward from Santa Fe, around the tip of the Sangre de Cristo Mountains, through Las Vegas, around the base of the Ocaté Mesa, past the home of famous Indian scout Kit Carson in the southeast corner of Philmont (fig. 2), along the east edge of Philmont, and thence northeastward along the base of the Park Plateau to Raton and the East. Deep wagon ruts of the old trail can still be seen in a few places. The pioneers chose the easiest route, and it is not surprising that the modern highway

corner of Philmont. Most visitors come into Philmont from Raton over U.S. Highway 64, which enters the area of the model about at the center of its east edge. The highway swings sharply west and passes through Cimarron town, by far the largest permanent settlement. For 50 years after its founding by Lucien Maxwell in about 1860, Cimarron was a major trading center, and it once had a population of several thousand. In this century, the year-round population of the town has declined and is less than a thousand, engaged mostly in ranching.

From the highway in the center of Cimarron town, we have a good view of the entire Philmont area (fig. 3). The highway and the town are on a plain at the inner edge of the Las Vegas Plateau. The mesa lands on the right (north) skyline are part of the Park Plateau, the southern tip of which is at Deer Lake Mesa, on the left (south) side of the highway. The flat-topped benches behind the town are a high part of the gravel-clad Las Vegas Plateau. Beyond them, and filling the whole center of the view, is the dark, forested mass of the



KIT CARSON'S HOME, now a museum, near the old Santa Fe Trail in southeastern Philmont. (Fig. 2)

Cimarron Range. Extending eastward from the main mountain front is light-colored Tooth of Time Ridge. At its base, hidden from view by intervening high graveled plains, are the three headquarters areas of the Philmont Scout Ranch. On the skyline at far left is the dark smooth surface of Urraca Mesa, in the southeastern part of Philmont and at the north edge of the Ocaté Mesa.

By hiking or driving westward from Cimarron on Highway 64, we can get a good idea of the landscape of the entire Philmont area. (In the first half of the century, when gold mining was active around Baldy town and on Ute Creek in the northwest corner of Philmont, we could also have taken the train as far as Ute Park; but the railroad stopped running when gold mining ended at the start of World War II, and later the tracks were removed. The old roadbed and the scars of the tracks can still be seen in many places near the highway.) A mile out of town the edge of the high mesa lands of the Park Plateau flanks the right (north) side of the road. The lower plains continue on the south side, but within another mile they begin to give way to hills. Four miles out of town the plains disappear, and the road is flanked on both sides by hilly ground.

The hills on opposite sides of the highway are very different. On the right (north) they are the same mesas or benchlands that we saw when we were first leaving town. The benches appear smooth, and the risers between them are steep but also smooth. Lightly sprinkled with bushes and clumps of grass through which alternate light and dark ledges of rock appear, the benchlands look striped. On the left (south) the hilly country is rough and irregular and is pitted by many small depressions (fig. 4). The hills are covered with dense brush broken by many small stands of trees. This contrast in landscape continues for 5 more miles.

Nine miles west of Cimarron the country opens out into another lowland like that around Cimarron, but much narrower. This is the valley of Ute Creek (fig. 5). Rising above the valley on both sides are hummocky, irregular surfaces like those that we have previously seen flanking the south

PHILMONT from the east. (Fig. 3)

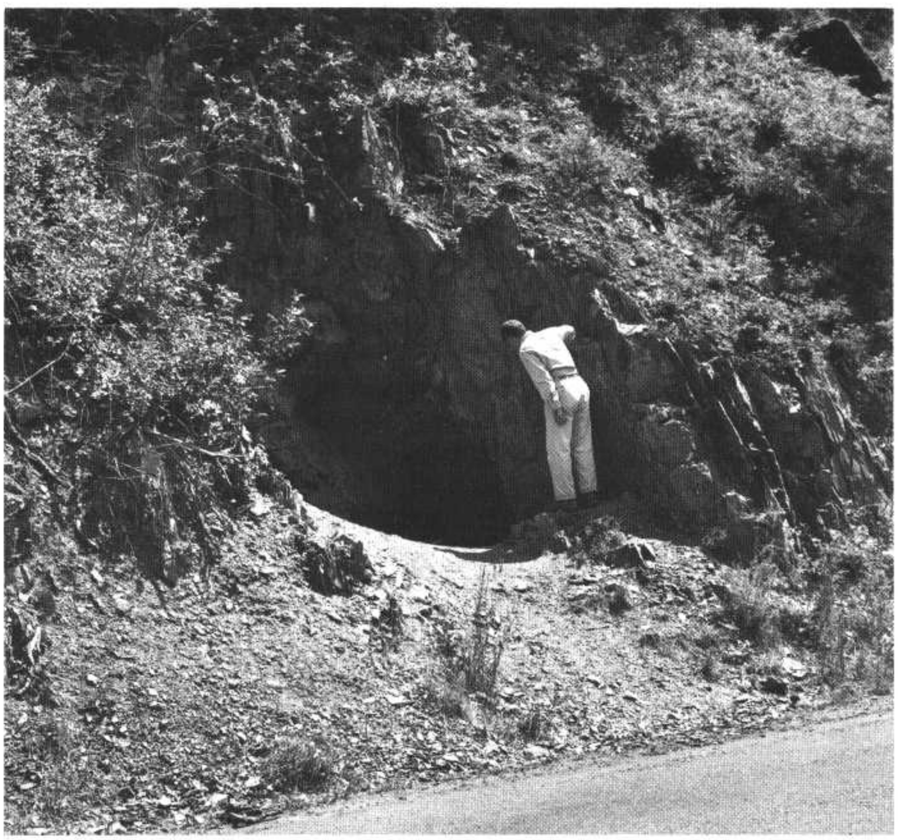
ROUGH, HUMMOCKY HILLSIDES
south of U.S. Highway 64. (Fig. 4)

side of the highway. At the tiny settlement of Ute Park, the plain ends abruptly, and the road enters canyon country (figs. 54, 65). Great rocky ledges separated by grassy and tree-lined vales and saddles rise on either side of the road. The streams run in sharp narrow canyons, and the heights are sharp and narrow, too. The country is all angles the rest of the way to Horseshoe mine—really just a prospect pit—at the west edge of our area (fig. 6).

Along the trails up other creeks at Philmont, we see similar landscapes. On Ponil Creek, north of Cimarron, the trail begins on the plains; but the plains narrow rapidly, so that 3 miles from Highway 64 the trail is in a narrow canyon flanked by striped benchlands. The trail continues in this type of terrain to the edge of the area. Beyond, it eventually enters rugged mountain country. All the land drained by Ponil Creek and its tributaries—nearly half of Philmont—is a country of narrow canyons separated by broad steplike benches. Figure 7 is a photograph taken on the top of one of these high benches.

The trails up creeks south of Cimarron Creek, such as Cimarroncito Creek, Urraca Creek, and Rayado Creek, pass through the same sequence of country as that on the south side of Cimarron Creek: first, broad lowland terraced plains such as those in the southeast corner of Philmont (fig. 8); then rough, hummocky hillsides capped by rocky upland benches; and finally, rugged mountain country that has no flatlands (fig. 9). Along two creeks in the heart of the mountain country, however, is a different kind of landscape: marshy meadowlands dotted with ponds and with clumps of trees (fig. 10). Long strips of such peaceful meadows flank Bonito Creek for several miles downstream from Beaubien Camp and flank Agua Fria Creek upstream from Rayado Base Camp. But downstream from Rayado Camp, the mountains close in (fig. 11); and Agua Fria Creek and Rayado Creek, after joining, run in a rocky canyon for many miles. Bonito Creek, too, pours into a gorge near the mountain front.

LOOKING NORTH UP UTE VALLEY to Baldy Mountain. The ghost town of Baldy is on the east flank of the mountain. (Fig. 5)



HORSESHOE MINE, beside U.S. Highway 64 where it crosses the west edge of Philmont. (Precambrian metamorphic rocks.) (Fig. 6)

ON MESA above Old Dean Trail Camp. Baldy Mountain in the background. (Fig. 7)

STEPLIKE TERRACED PLAINS in southeastern Philmont. View is southeast from near gaging station on lower Rayado Creek. Kit Carson Mesa in middle distance. Highest surface is Gonzalitos Mesa, beyond Philmont. (Fig. 8)

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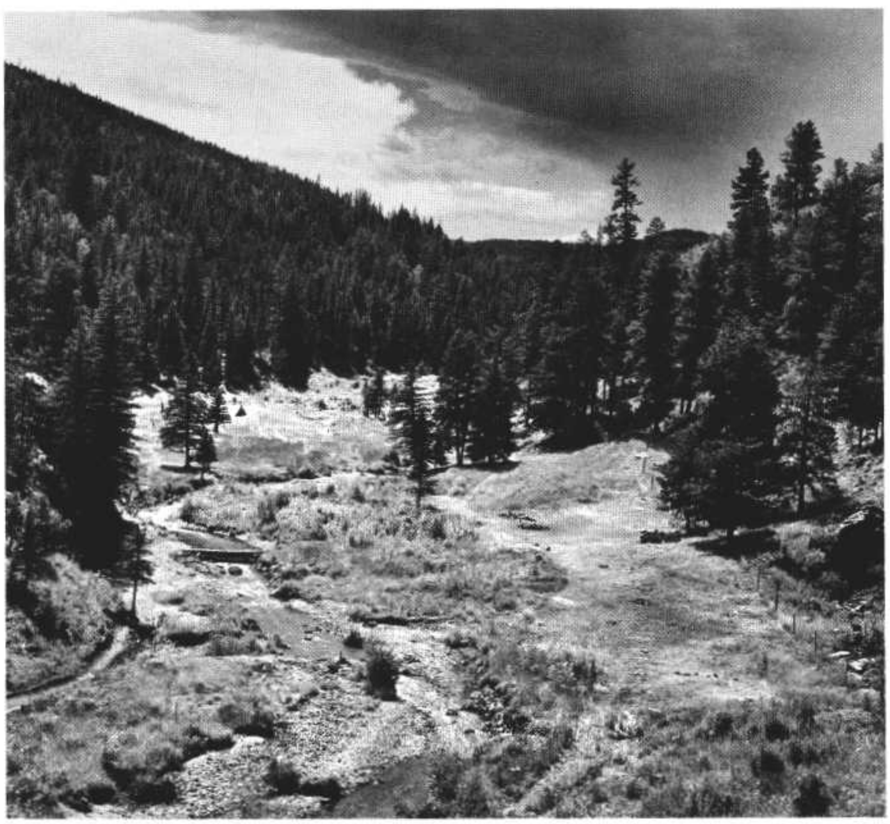
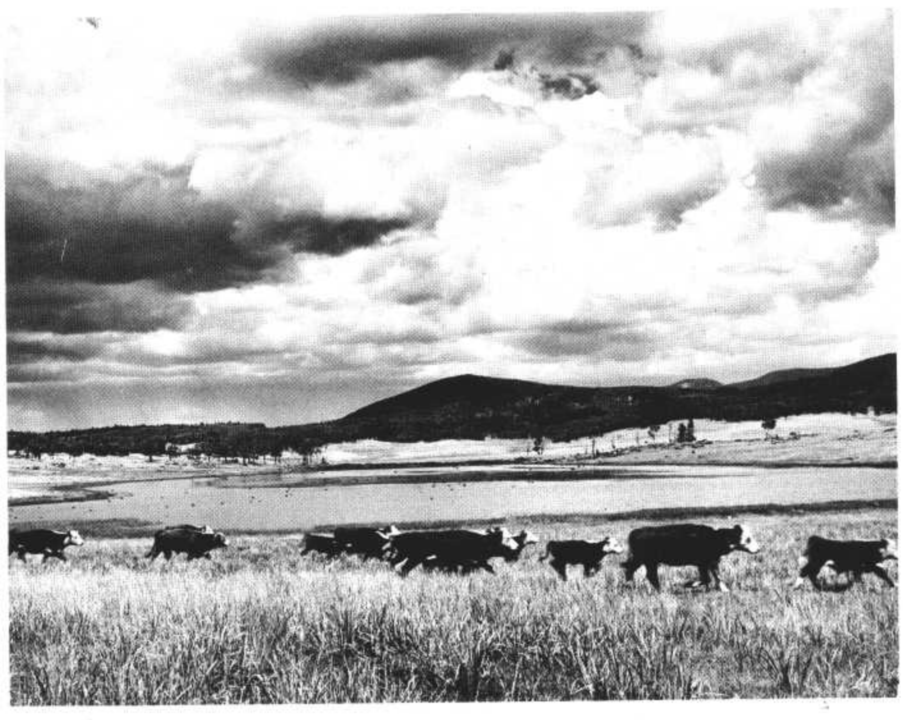


RUGGED MOUNTAIN COUNTRY in west-central Philmont: Bear Mountain (rounded top) and Black Mountain (pointed) viewed from Cimarroncito Base Camp. (Fig. 9)

MARSHY MEADOWLANDS along Agua Fria Creek upstream from Rayado Base Camp. (Fig. 10)

MOUNTAIN VIEW EAST from Rayado Base Camp, where Agua Fria Creek joins Rayado Creek and flows in a narrow rocky canyon. Sunlit rocks (Precambrian metamorphic rocks) are on the flank of Lookout Peak. (Fig. 11)



HIGH MARSHY MEADOWLANDS on the Ocaté Mesa. (Fig. 12)

The southernmost trail in the Philmont region follows Moras Creek upstream to the steep front of the Ocaté Mesa and then wanders across the mesa. For several miles this trail, too, crosses familiar scenery: first the lowland plain flanking Moras Creek, rising in three bench steps to rough, hummocky hillsides along the mesa front; and then a rocky bench atop the mesa. The benchland at the mesa edge is definitely darker colored than that far to the north, but the shapes are similar, if a little more rounded. Westward, however, to Rimrock Lake and beyond, the trail crosses many marshy meadowlands, like those of Bonito and Agua Fria Creeks but much broader and more irregular (fig. 12).

We have seen that the landscape can be divided into five main kinds of landforms: gravel-capped lowland plains; smooth-sided rocky benchlands; rough, hummocky hillsides; rugged mountain country; and high marshy meadowlands. These are shown on a scale model, plate 1 in the back pocket. The model is drawn as it might look to a bird hovering high above the southeast corner of Philmont. How each of these forms came to be, we will learn as our story unfolds. It is not just a matter of height above sea level, for there is much overlap in altitude among the five kinds of landforms. We can see already that the rocks beneath the land are somehow related. Before turning to the rocks, however, we must look at another major landscape feature—the water on the land.

GEOLOGICAL SURVEY STREAM-GAGING STATION on Cimarron Creek. A, Cable car used when measuring the rate and amount of water flow. B, Depth-recording gage. (Fig. 13)

Water on the land: Creeks and lakes

After a heavy rain or after the spring thaw, water runs off every slope and pours down every gully and canyon; but for long periods in summer and winter, all the gullies and most of the short canyons are dry. In the long canyons, creeks usually flow all year round, although most of the flow comes in the 4 months, April to July. After spring thaws or heavy summer rains, the main streams may for a few days discharge so much water that they overflow their banks and flood their valley floors. The rest of the year they dwindle to a trickle; sometimes they even run dry.

The details of streamflow are very important to everyone living in the area; for this is dry ranching country, and the streams are a main source of water for drinking, waste disposal, and irrigation. To measure streamflow accurately, the U.S. Geological Survey maintains stream-gaging stations on Cimarron, Rayado, and Ponil Creeks. Figure 13 shows what such stations look like. The depth of the water at each station is automatically recorded by a gage (fig. 13*B*), and the rate and amount of water flowing past the gage is measured, usually twice a month, by an observer, using a hand-powered cable car (fig. 13*A*) who makes measurements at midstream. Several thousand such stations are operated all over the United States.

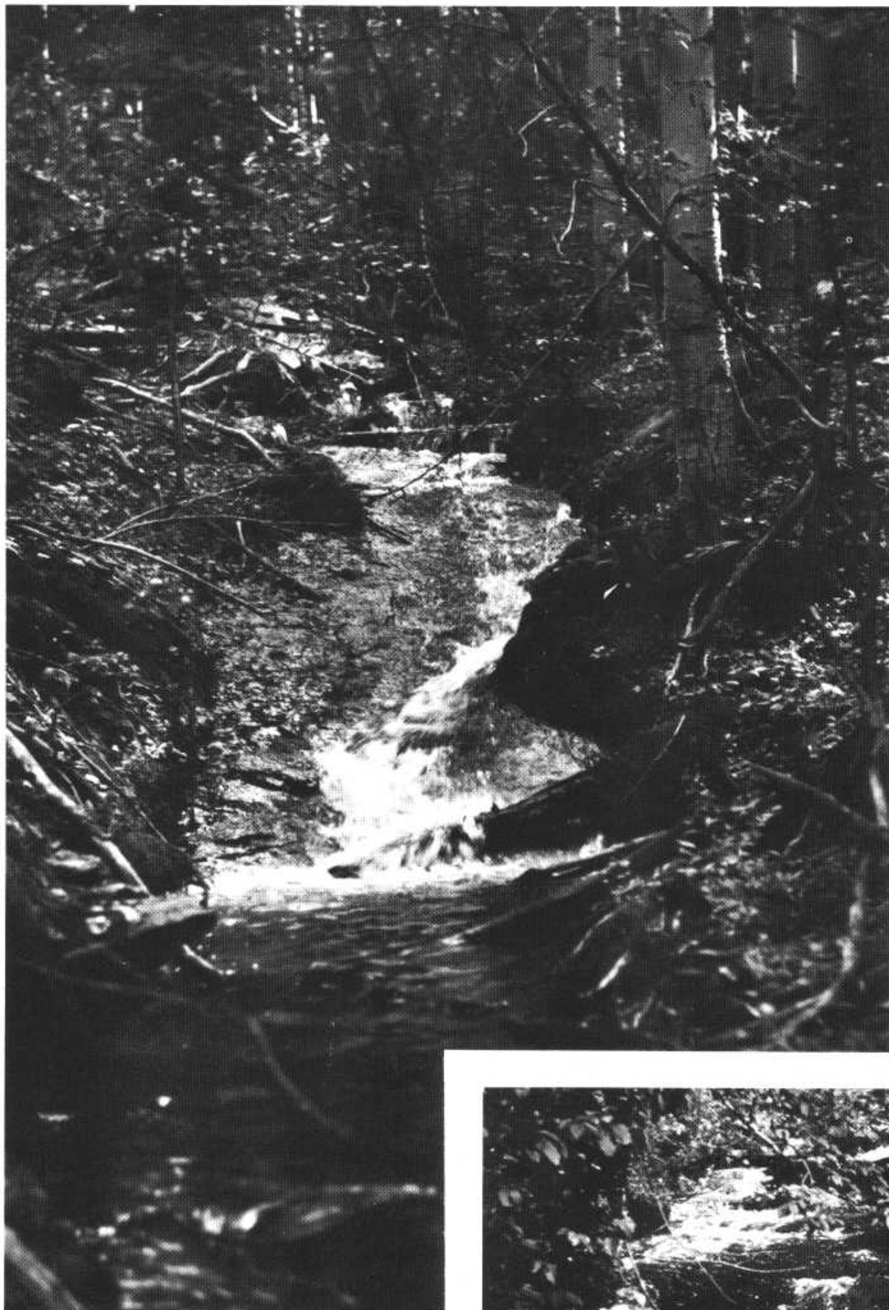
The intermittent creeks get all their water from rain or melted snow. They run dry soon after a rain stops or after the snow melts. The creeks that keep flowing through dry spells have more sources of water than just that which runs off the surface. Cimarron Creek gets much of its water from Eagle Nest Lake in Moreno valley to the west; Agua Fria Creek, in the southwest corner of Philmont, is partly fed from Agua Fria Lake. The other perennial creeks, such as Ponil, Cimarroncito, Urraca, and Rayado Creeks, start from gullies on mountain sides and are fed downstream by springs that gush or seep out of the rocks.

Creeks in the high mountains run straight and swift in narrow V-shaped valleys (fig. 14). Down stream, but still in the mountains, the valley bottoms of the larger streams flatten, and the creeks flow smoothly as they wander from side to side on the valley floor (see fig. 10). Where the streams cross rocky ledges at the mountain front, their valley walls close in, and their beds become very rough, having alternate riffles, pools, and falls (fig. 15). Most of the waterfalls, like the one pictured, are only a few feet high; but one on South Fork Urraca Creek, near where the trail to Crater Lake Base Camp crosses the creek, is more than 50 feet high. As the streams leave the mountains and flow through the benchlands to the plains, rapids and falls disappear, and the streams again flow quietly, meandering on valley floors that widen downstream (fig. 16).

The perennial streams and their larger tributaries are arranged like the veins of an oak leaf or the branches on a piñon pine: where they meet, they form V's that point downstream. Even the smallest gullies have this pattern in most of Philmont; but along part of the mountain front, between Cimarroncito Creek and Ute Park Pass, the pattern of the small streams is different. There, the streams run about parallel to the mountain front and to each other.

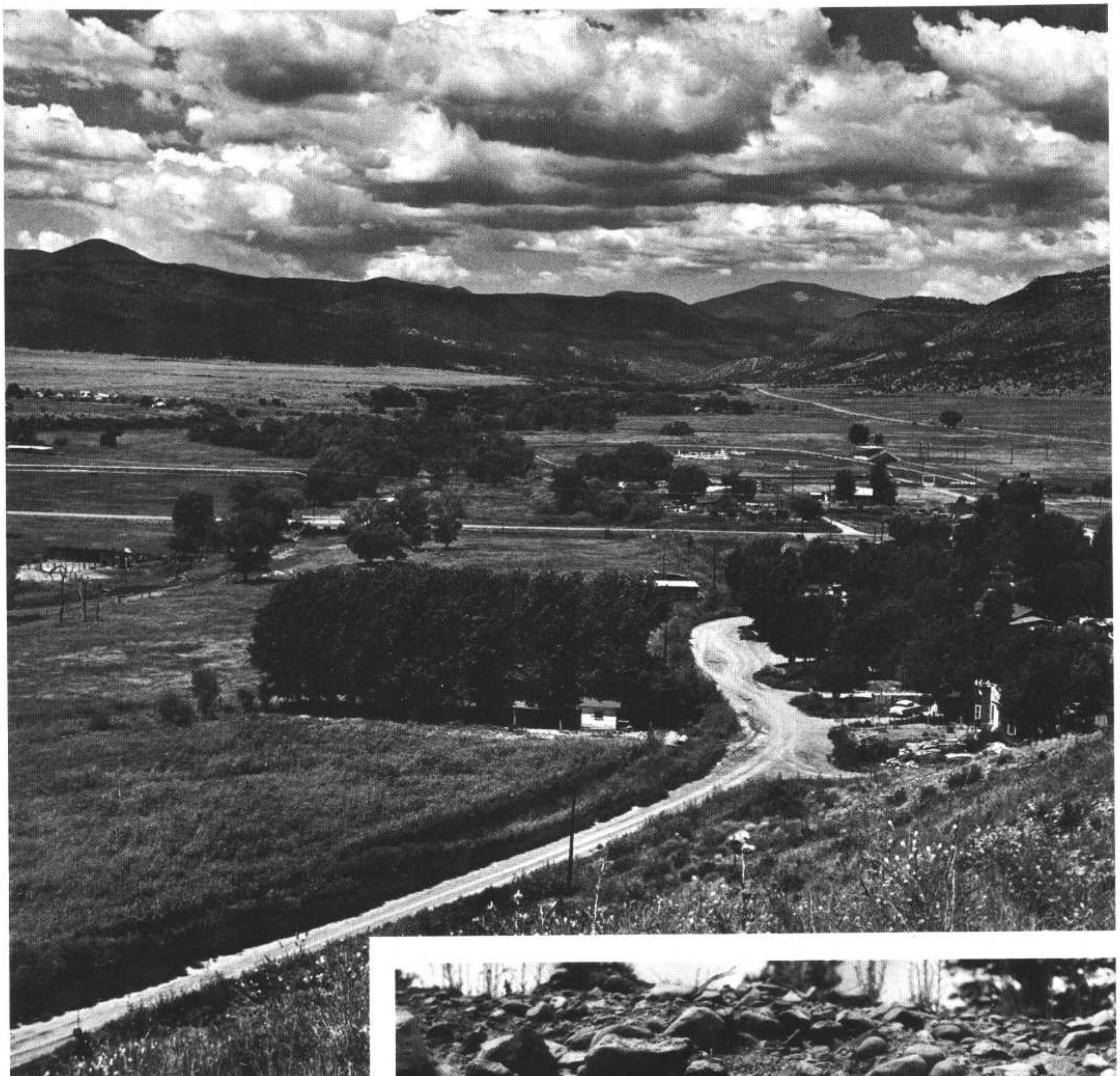
Knowing that water flows downhill, we naturally expect the streams of Philmont to flow away from the crest of the Cimarron Range. Nearly all of them do, but not Cimarron Creek. Starting at Eagle Nest Lake in Moreno Valley, it flows right across the range. It is, therefore, by far the longest stream at Philmont and the master stream of the area. All the other streams join it in or near Philmont, and the combined flow enters the Canadian River, 20 miles to the east. Eventually, the water that flows out of Philmont ends in the Gulf of Mexico, after a 1,500-mile trip by way of the Arkansas and Mississippi Rivers.

Even the few creeks that flow westward off the map area are tributaries of Cimarron Creek.



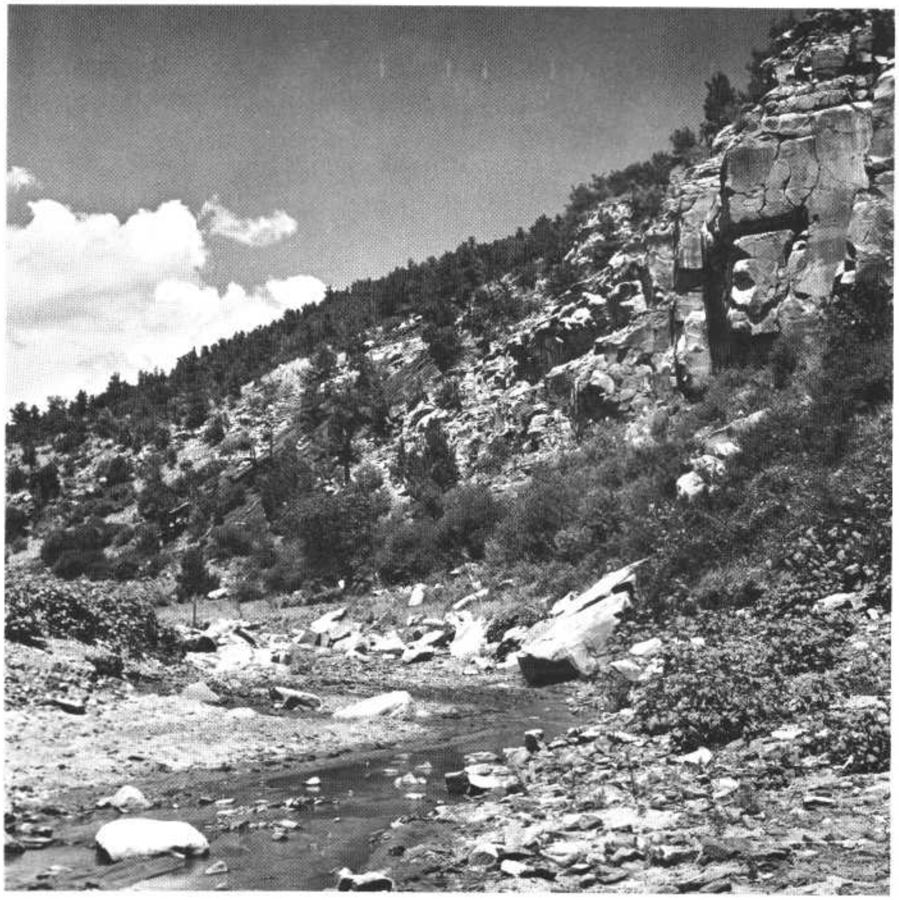
NEAR THE HEAD OF A TYPICAL STREAM in the mountain country. (Fig. 14)

WATERFALL ON RAYADO CREEK near Crater Peak. (Fig. 15)



BROAD VALLEY OF CIMARRON CREEK on plains east of the mountain front. (Fig. 16)

PEBBLES AND COBBLES of sandstone and dacite porphyry—a rock like granite—form the bed of Cimarron Creek near Cimarron town. (Fig. 17)



SHARP-EDGED CHUNKS OF ROCK (Trinidad Sandstone) that have recently fallen into the bed of Ponil Creek. (Fig. 18)

The creeks that drain the west flanks of Baldy Mountain, Touch-Me-Not Mountain, and Tolby Peak descend into Moreno Valley and then turn and flow into Eagle Nest Lake. From there these waters start their long eastward journey down Cimarron Creek. How Cimarron Creek came to flow across the Cimarron Range in such a roundabout course, we will go into later.

In times of flood, the creeks do more than drain the water off the land. Most of the time, Cimarron Creek, for instance, is a clear quiet stream only a foot or two deep and two jumps wide. As it flows smoothly over its gravel bed, it sweeps along only a little sand. But after a heavy rain or thaw, it swells into a swirling, roaring flood that has frightening power. The creek becomes a thick sludge of sand, mud, and plant debris. Large stones thunder and rattle as they are swept along the bottom, crashing against the stream bed and each other. Where the banks are steep, the water piles high; where they are low, the torrent leaps them and spreads into a thin turbulent sheet. As the flood recedes, we can see that the creek has cut into its banks and bed in some places, especially on the outside of wide swings, or even has cut a new channel. In other places, it drops its load—first the boulders, then the cobbles, and then the sand and mud, as the speed of the water slackens. In this way, by sidecutting here, filling there, and shifting its channel in storm after storm, the creek widens and smooths its flood plain.

Many of the stones in the creek bed have come a long way (fig. 17). Near Cimarron the creek flows between banks of soft black shale, but the stones it moves are not shale; they are mostly hard yellow or white sandstone and salt-and-pepper-spotted dacite porphyry, a rock like granite. Outcrops of yellow sandstone are nearby, but we must go to the mountain front, at least 11 miles upstream from the town, to find the creek running near ledges of dacite porphyry, and still farther to find white sandstone ledges. In the mountains, the stones start their journey as sharp-edged chunks of all sizes that break off bedrock ledges and roll or slide into the creek (fig. 18). As the chunks are moved farther downstream by flood after flood, impact with each other and with the rocky stream bed splits them into smaller and smaller pieces and rounds their edges a little.

A stream in flood is a mighty shovel, and the valley in which it runs is not just a "low place" to which water flows but rather is low because water has long flowed through it. The stream deposits show this, but their evidence is not really needed to prove that streams generally make their own valleys. Almost everywhere at Philmont and, in fact, the world over, streams join each other smoothly, having neither pools nor falls at the junction (fig. 19). If the valley of each stream were not cut by the stream itself, but were a crack in the earth's skin due, for instance, to the drying out or the upheaval of rocks, this would certainly not be so. Instead, most junctions would be marked by cliffs which, depending on whether the cliff faced upstream or downstream, would pen lakes or make waterfalls. Cracks in the earth's skin may, however, give streams a place to start. Where stream junctions are not smooth, we may suspect that other agents besides running water have been at work.

Thinking of streams in this way, and realizing their power to erode, we may well wonder that the Cimarron Range, or any mountain, stands above the sea. Where mountains remain, the streams have not finished their work, either because they have not had time enough or because processes in the earth work against erosion to keep mountains high. The geologic story of Philmont is mainly the record of interplay among the little-known processes that make mountains and the less mysterious ones, mainly stream erosion, that destroy them.

Not all the rain or melt water flows off the surface. Much of it stands in thousands of low places all over Philmont. Most of this standing water disappears within hours or days, partly by evaporating and partly by sinking into the ground. Only about 20 bodies of water are large enough and persistent enough to be thought of as lakes. Of these, only four are year-round natural lakes: Deer Lake on Deer Lake Mesa, Crater Lake at the east base of Trail Peak (fig. 20*A*), and Agua Fria and Rimrock Lakes on Ocaté Mesa (fig. 20*B*, *C*). The others, such as Webster Reservoir, Hagerdon Lake, and Miami Lake, are man made.

The lakes, whether natural and artificial, will not last long, in

TYPICAL JUNCTION of streams. (Fig. 19)

NATURAL LAKES of Philmont. A, Crater Lake. B, Agua Fria Lake. C, Rimrock Lake. (Fig. 20)

terms of geologic time. The creeks flowing into them bring in gravel, sand, and mud; a lake, therefore, slowly disappears by filling, in from the sides and up from the bottom. When the water is low, we can see how the filling process works (fig. 21). Spreading from the mouth of each creek is a low bulging fan-shaped mass grooved by fingerlike channels. This fan-shaped mass has been dumped by the creek as it lost its speed, and therefore its ability to carry a load, when it flowed into the standing lake water. The finger-like channels mark the final path of the flowing water before it merged with the lake water. In these channels are the coarsest materials—gravel and sand. Beyond the fingers are the finer materials that could be carried farther—silt and clay. As the shape and size of the lake changes, the pattern in which creeks entering the lake spread their load changes too; so that stringers and patches of different kinds of rock waste alternate with, and grade into each other, and the lake

slowly fills. Eventually, it may become too shallow to hold the creek waters, and they will pour over the lowest point. Regaining speed because of the increased slope, they will cut away at the outlet, draining the lake and trenching the lake deposits, until the former lake becomes part of the stream valley.

Long before a lake is destroyed by filling or by overflow, however, there is a good chance that it will be destroyed by other natural enemies. It may die slowly, its rim breached by a stream from below, as in the diagram (fig. 21), or it may die quickly, its rim broken by earth movements or the failure of a dam. For instance, the topographic map shows that large but seasonal La Grulla Lake, on the edge of the Ocaté Mesa south of Rayado Base Camp, will be drained before long by the stream that has already deeply notched the nearby mesa rim.

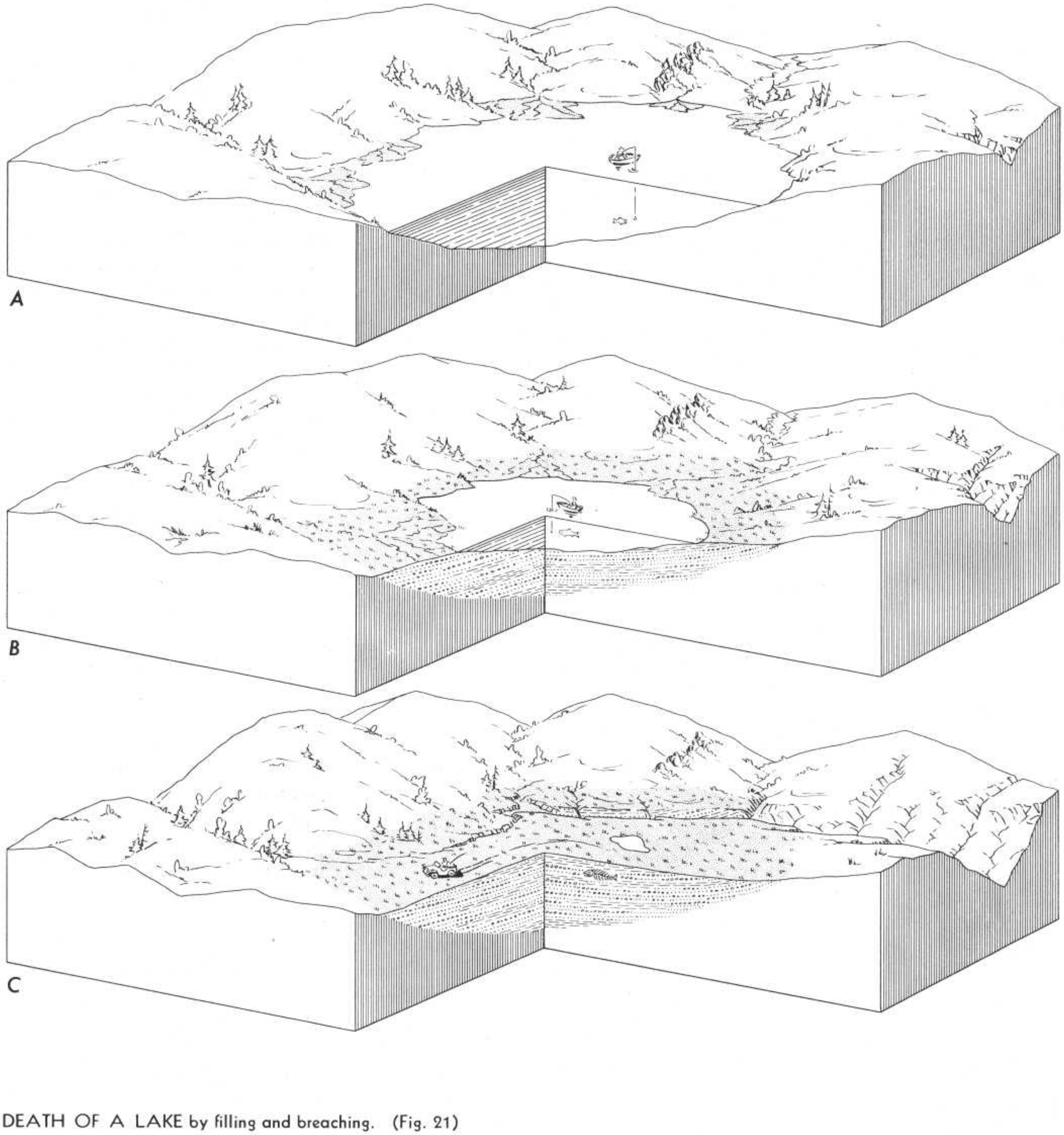
Climate

On the plains and lower mesa lands, the climate is semidesert. Most of the landscape, covered with short grasses, is a dull yellowish gray except where man has cultivated it. Scattered about the grasslands are clumps of dry-country shrubs such as cactus, greasewood, rabbit brush, sagebrush, and yucca. Almost the only trees are cottonwoods and willows, which are along streams. Cimarron, where the U.S. Weather Bureau has long had a station, has about 16 inches of rain and melted snow in an average year. This is more moisture than deserts receive, but it is not enough to insure crops without irrigation. About half the water that falls on the plains comes as afternoon rains in spring and fall. Snow falls from October through May and usually totals about 40 inches (1 foot of snow is equal to about 1 inch of rain). There are about 70 rainy or snowy days each year at Cimarron—less than 1 in 5. Though the plains are dry, they are not hot because they are more than a mile above the sea. Once in a while it gets as hot as 96°F. in midsummer, but the highest summer temperatures are generally in the 80's. Winters on the plains are cool: afternoon temperatures are in the 50°'s or 60°'s, and those at night are often below freezing but rarely below 0°F.

In the higher country the climate is markedly different. Days and nights are much cooler than on the plains. Much more rain and snow fall, maintaining a rich forest cover, mostly of evergreen pine, juniper, spruce, and fir but including many seasonal trees, especially oak, cottonwood, aspen, and alder. There are probably more than 100 rainy or snowy days each year at altitudes above 9,000 feet, but even at that altitude 3 days out of 4 are sunny and pleasant. The prevailing color in the mountain country is dark green. At highest altitudes, however, the green cover thins out and patches of drab color and bare rock are common. This is not because there is not enough water to feed plants, but because it is too cold and too windy for them to get a start.

In the northern part of Philmont, the change from plains climate to mountain climate is gradual because the altitude changes gradually. In the southern part, however, the plains pass abruptly into mountains, and the changes in climate and vegetation are equally abrupt.

Plants and animals are certainly part of any landscape, but those of Philmont are not discussed in this book because they are described in "Philmont Nature Story," published in 1960 by the Boy Scouts of America. Drawings of a few of Philmont's animals are, however, scattered through this book.



DEATH OF A LAKE by filling and breaching. (Fig. 21)

A CLOSER VIEW: The rocks, fossils, and water beneath the land

Coming closer to the ground, we discover that Philmont has a dazzling variety of rocks—the materials of the earth's hard skin. Every kind of rock that is common on the earth as a whole is present here, as well as some rare types. Naming rocks is not easy, for in the realm of rocks, as in all natural realms, there are few sharp divisions. Rocks grade by small changes in appearance and composition into other rocks. Geologists give them definite names and arrange them in classifications in the hope of finding hidden order in outward chaos. In our search for order, we will divide the rocks of Philmont into about 20 types. The names they are given are convenient handles; not all should be taken very seriously.

The origin of rock names is a fascinating subject in itself, but one we will not go into very far. Some names are descriptive: the name "granite," for example, given to a certain rock made of coarse crystal grains, stems from the Latin word *granum*, meaning grain; and the name "schist," given to a finely layered crystalline rock that splits easily, comes from the Greek word *schistos*, meaning divisible. Other rocks are named for places where they are common—dacite is named for *Dacia*, a Latin name for lands that are now part of Romania. Still other rock names, such as basalt, are so old that their origins are forgotten.

Only about half a dozen of the 20 named rocks are important in volume. The rest are interesting curiosities which happen to be fairly easy to see and reach. Some others, just as interesting, are not mentioned because they are hard to see or to reach.

A rock is simply a natural mineral collection. Nearly all rocks are made of crystals or fragments of several minerals; a very few are made of many crystals or particles of a single mineral. The minerals in rocks are not often easy to recognize, even for mineral collectors, as they are seldom in large well-shaped crystals of the sort usually pictured in books or displayed in museums. Large well-formed crystals are rare—that is why they are collected and exhibited. The minerals in most rocks are in small grains that have poor crystal outlines or none, owing to conditions of growth or to wear. To help identify the rock-forming minerals of Philmont and the rocks they form, all the minerals and rocks mentioned are illustrated by photographs of ordinary specimens.

Fossils are parts of rocks, and they tell a great deal about conditions when they were buried. Therefore, fossils are discussed along with the rocks in which they are found. They too are illustrated, but we are not so generous with information on hunting grounds—these you will have to find for yourself! Soils are rocks, too, and an extremely valuable kind to man; but we will have nothing to say about them because we did not study them.

If we are to make more than a geologic shopping list, we must not only find and name the main rocks but also decide how they formed and when. "When," we will leave until a later chapter. "How," we will consider briefly for each rock. For most rocks, this is not a mere guessing game, though we have space to present only a little of the evidence.

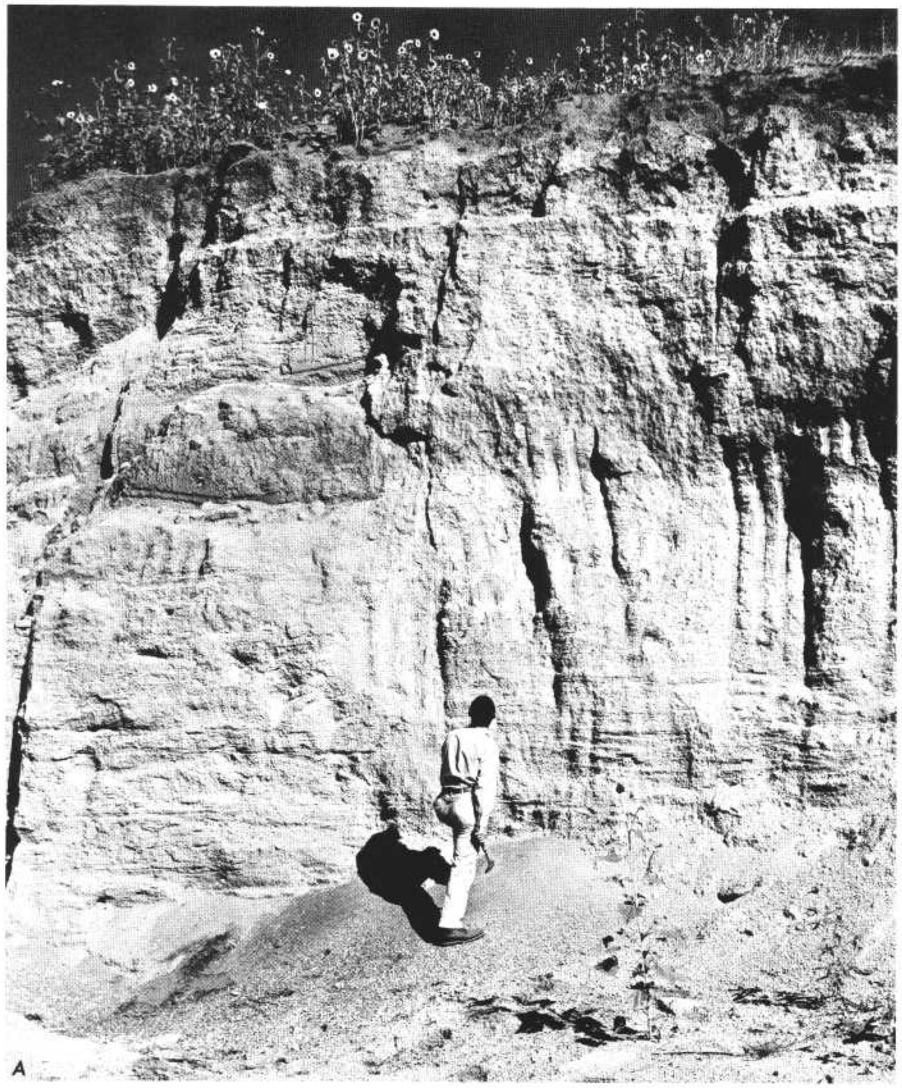
Many common rocks can be caught in the act of forming. For example, every few years white-hot lava pours out on the earth's surface in such places as Hawaii and Mexico, and freezes to black basalt. On any beach we can see sand being rounded and sorted by waves and currents, and we can observe the kinds of animals and plants that live and are buried there. If the basalt that has cooled before our eyes is in nearly every way like a rock long cold, then the old rock may also be basalt that poured out on the surface. A sandstone that is identical, except for the cement that holds the sand together, with beach sand in which we have dug, and has in it the remains of animals like those we have seen on beaches, probably formed on an ancient beach. If the basalt is now covered by other rocks, so that it is no longer obvious that it flowed on the surface, or if the sandstone is far from the sea, we need not decide that the other direct observations are worthless. Rather, we conclude that much has happened to these rocks since they formed. In thus using what is known from direct experience to interpret events distant in space or time, we are using both simple common sense and a basic scientific principle that goes by the name, "uniformitarianism."

The method of learning about the faraway and long ago by comparison with the near and present works well for events that can be watched, but not all geologic events can be observed. Some natural processes—the building of a mountain range or the evolution of an animal species—take so long that direct comparison based on experience is impossible. And many events of geologic importance take place only far below the surface, beyond observation. Certain rocks, for example, have never been seen forming at the earth's surface. Even if they are now forming deep below the surface, we cannot watch what happens, and there must always be some doubt about their origin. But we can learn much even about slow or hidden happenings by studying related natural processes and events that can be observed and by making laboratory experiments under conditions that are thought to exist naturally but that cannot be observed.

The common coarse-grained crystalline rock called granite is an example. Although it has never been seen forming, some of it, at least, surely forms by the cooling of a rock melt deep within the earth's crust. This seems a safe conclusion because lava of the same chemical composition as granite, and containing the same minerals, has often been seen flowing from volcanoes and cooling on the surface to become the rock called rhyolite. The only difference is that the lava is made of tiny crystals, whereas granite is made of much larger ones. As everyone who has made fudge knows, the slower a melt cools, the larger the crystals that grow from it. Therefore, it is reasonable to think that granite may form from the slow cooling of a melt like that of rhyolite. And a rhyolite melt will cool slowly if it is under a thick insulating blanket of rock—that is, deep below the surface.

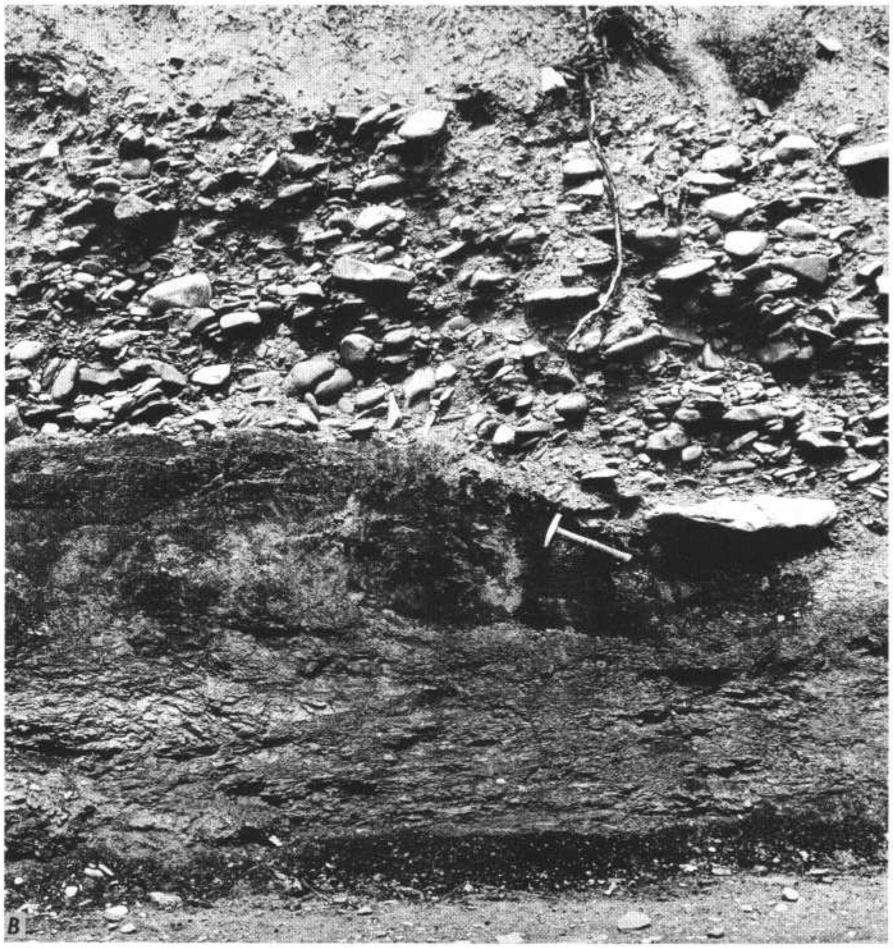
We can go farther. In the laboratory, practically all the conditions that are likely to exist anywhere on the earth's surface or in its outer crust can be reproduced, though on a very small scale. We can actually find out how granite or a granite melt behaves in the laboratory and gain many clues to the way it behaves in nature. So by using as many direct observations as possible and as many indirect ones as necessary, we can come to conclusions of varying certainty about the ways in which rocks have formed, at Philmont and elsewhere.

* * * *



GRAVEL AND SAND: mementos of ancient floods. A, Excavation in clayey sand and pebble gravel on flood plain of Urraca Creek below the Stockade. B, Roadcut in gravel overlying coal and shale (Vermejo Formation) along lower Ponil Creek. (Fig. 22)

The bird that observed the landscape of Philmont flew on a zigzag course from east to west, from the plains to the mountains. In examining the rocks beneath the landscape, we will follow the same path, though, of course, more slowly.



Rocks beneath the plains

Gravel and sand

Rounded gravel and sand cap the plains around the Ranch headquarters and Cimarron town and also the long narrow flats along the larger streams in the mountains. On the plains and flats, the gravel and sand are mostly hidden by soil, but they can be seen wherever cuts have been made by streams or by man (fig. 22). Although there may be more sand than gravel, the sand makes poor outcrops, and it is easy to get the idea that the capping material is nearly all gravel. Natural and man-made cuts reveal that the gravel-sand blanket is usually only a few feet thick and that it lies mostly on soft black shale. Thin as it is, the blanket contains a vast amount of rock, for it covers 50 square miles on our map and many times that to the east.

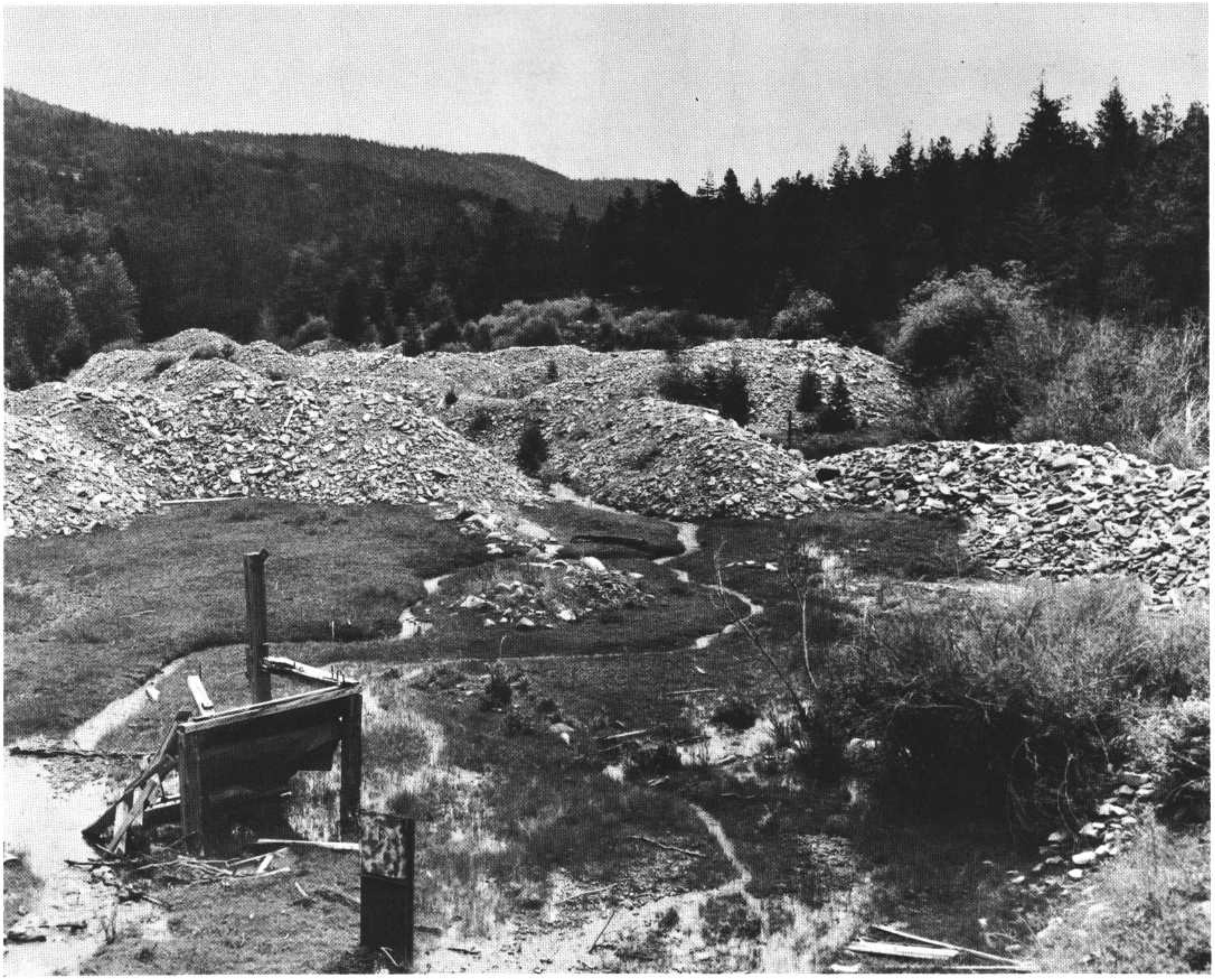
The gravel and sand on the plains are exactly like their counterparts in the beds of the creeks and surely formed in the same way: by settling out of flooding, shifting streams. Such deposits, which have settled out of running water—or out of any other transporting medium: lake water, sea water, wind, glacier ice—are called sediments. The plains beneath these sediments, then, are ancient stream flood plains. To build them must have taken a very long time, for the few floods each year can lay down only a little sand and gravel, and much or all of that may be swept away by later floods. How the sediments on the plains came to be high above the present streams is part of the story of landscape sculpture that will be told later.

Along Ute Creek, especially above Atmore Ranch, the gravel capping is not a smooth flat-topped soil-covered layer but stands in bare mounds as much as 20 feet high, so that the valley looks like a giant gopher prairie (fig. 23). The mounds are stream gravel that has been churned up by floating gold dredges. Gold was discovered in the gravel of Ute Creek late in the last century and has been mined intermittently ever since, both by dredges, when there was enough water to float them, and by hand methods. Several millions dollars worth of gold have been won from similar deposits on the west side of Baldy Mountain, near Elizabethtown, but the Ute Creek gravels were never very rich. In 1961, the rusted remains of the last dredge, long unused, still sat near the mouth of Ute Creek.

Miners who worked on Ute Creek still live at Cimarron. They say the gold was in flakes, chips, and small chunks lodged between the gravel stones; one nugget weighing nearly 12 ounces is said to have been found in the 1890's. The valley is about worked out, but gold "colors" can still be panned from the creek.

Like the stones of the gravel, the gold was washed off the mountains upstream. Because gold is so heavy, very small pieces settled out along with the coarse gravel, while the small bits of lighter minerals were swept on downstream as sand and mud. Such water-laid deposits of heavy minerals are called placers.

A large part of the world's gold production has come from placers.



GRAVEL MOUNDS made by gold dredges along Ute Creek. (Fig. 23)

The famous gold rushes of history started with the discovery of placer gold, for anyone can go placer prospecting with little money or knowledge; anyone with a mule or a gold pan and a little luck may make his fortune. In turn, many bedrock gold lodes have been found by tracing placer gold upstream to its bedrock source. (More often there is no rich source; instead, the gold is scattered in the rocks, and its richest concentration is in the stream gravel.)

Gold mining at Philmont went the other way, however. Gold, in veinlets and as thickly scattered specks, along with some copper and iron minerals, was found and mined high on Baldy Mountain in the 1860's; the first placers in the valleys below were discovered years later. For many decades both placer and bedrock mining came and went; at times a dozen mines were producing gold. During the great depression of the '30's, Baldy Town had a population of several hundred (fig. 24*A*); but as economic conditions improved, the miners left, and all the wooden buildings were moved. Today, nothing but a few stone ruins and mine dumps is left (fig. 24*B*).

Little is known about the bedrock ores. Written records are poor, and we have no first-hand knowledge; for when we were there all the mines on Baldy Mountain were caved in, flooded, or otherwise inaccessible. The mining areas, which are privately owned, are closed to visitors; this is just as well, for such mines are unsafe and should be avoided.

Gold is not the only heavy, tough, chemically resistant metal that is washed from sand and

BALDY TOWN. A, In 1939. B, In 1961. (Fig. 24)

gravel. Nearly all the world's production of platinum and tin comes from placers, as does much of the world's supply of diamonds and of other heavy precious and semiprecious stones such as rubies, sapphires, zircons, and spinels.

The main value of gravel and sand does not come from their rare and glamorous burden of heavy minerals. Gravel, of the right kind and quantity, is itself a major mineral resource. Around 700 million tons of gravel mostly for road construction, was produced in the United States alone in 1960 and had a value of nearly $700 million. This is many times the value of the United States' production of precious metals and jewels and of about the same order as the value of iron produced. By comparison, the United States produces only about 100 million tons of iron annually; however, since iron is worth much more than gravel, the total annual value of American iron is about $900 million.

The gravel at Philmont, though not much used yet, is a valuable mineral resource for the future.

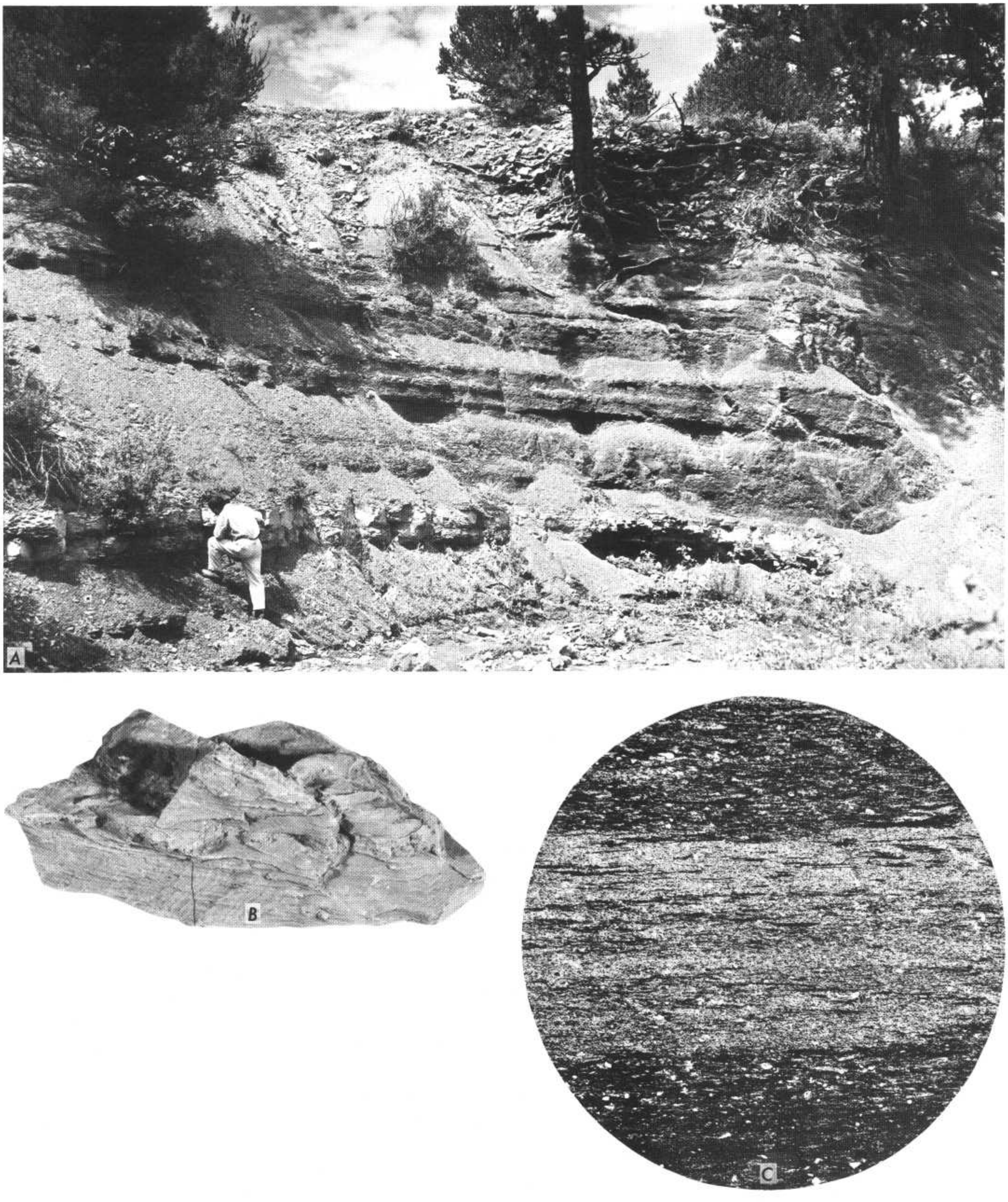
Black shale and orange shale

Beneath their blanket of gravel and sand, the plains are underlain mostly by dark-gray to black shale. This soft rock, which splits and flakes at the touch of a hammer, makes few ledges but appears in innumerable stream and road cuts. Good exposures, for example, can be seen in the banks of Cimarron Creek 1 to 2 miles upstream from Cimarron town and also on the main trail into New Abreu Base Camp (fig. 25). The fragments that make up most of this rock are too small to see, even with a pocket magnifier (fig. 25*B*); but when the rock is magnified enough (fig. 25*C*), it turns out to be made mostly of flaky plates of gray or brown clay and mica, tiny sharp-edged bits of colorless quartz, and black and brown clots of altered plant remains. Scattered in the rock are round white grains that once were single-celled living things called coccoliths. The shale began as mud—a sediment like sand and gravel but much finer grained. Now—dried, hardened, and compressed—its grains having been cemented together, it is rock. Such cemented sediments are called sedimentary rocks.

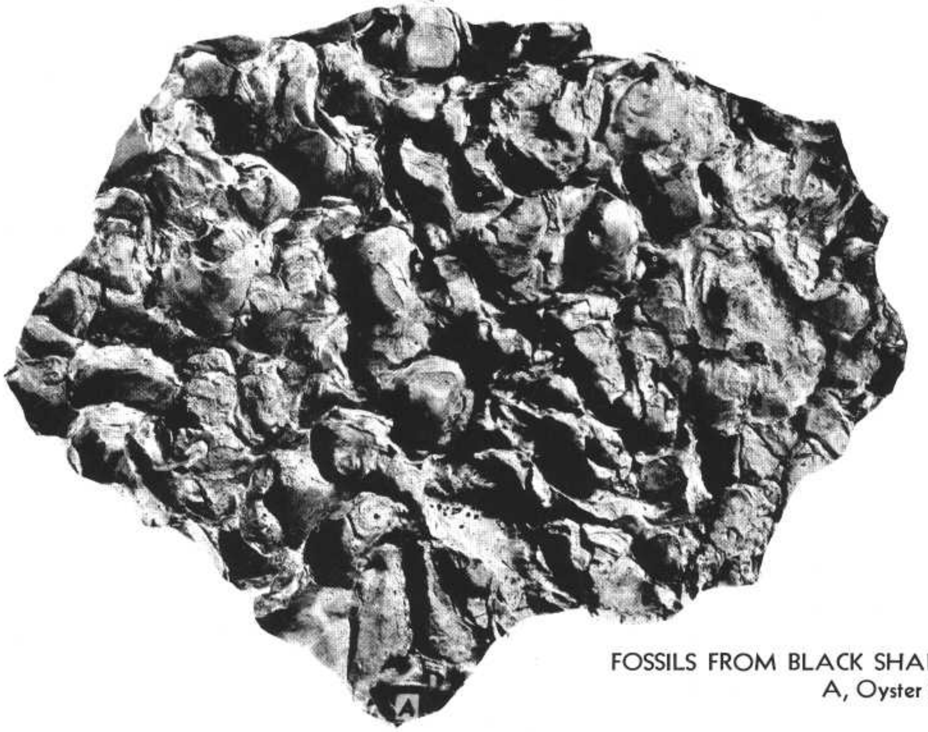
That life once flourished here when these rocks were mud is shown by more than microscopic fragments. In many places the shale contains the fossilized hard parts of many animals and the prints made by the hard or soft bodies of other animals that long ago decayed and vanished (figs. 26, 27, 28). The most abundant fossils, often encased in biscuit-shaped masses of orange-stained limestone, are shells. Most of the shells are of oysters and clams; some are smaller than a dime, and others are larger than a football (fig. 26). There are also the shells of many snails and of several types of extinct ammonites (distantly related to cuttlefish and squids); some are straight and shaped like a dagger sheath, some are tightly coiled, and all have marvelously complicated walls between the shell chambers (fig. 27). Quite different, and less common, are shark teeth—sharp incisors that have scalloped cutting edges like the edge of a bread knife, and stubby molars that have flat grinding surfaces (fig. 28).

These rocks are now much more than a mile above sea level and 600 miles from the nearest ocean water, but they began as mud on the ocean floor. The shale itself does not show this, for gray and black muds also form on stream floods plains or in lakes, as we have seen. Convincing evidence comes from the fossils. The snails and clams are of little help, as some snails and clams live in fresh water. But living oysters, sharks, and all relatives of the extinct ammonites live only in the ocean; and rocks which contain the remains of these animals must have formed in salt water. Some of the animals—the oysters and clams—lived and died where we find them. The ammonites and, of course, the sharks, were swimmers, and probably never lived in the mud; after the animals died, their hard parts settled down from above or were washed in. Muds like these are forming today in quiet waters along the Atlantic and Pacific coasts. We will soon learn how and when Philmont was beneath the sea and how and when it got so far from salt water.

Standing out from the black finely layered shale are a few beds of orange shale, generally no more than a few inches thick. When these are wet, they swell up and become sticky because part of their clay is the swelling type called bentonite. Some pure bentonite rocks when wet swell as much as 60 times their dry volume and have many industrial uses, but those at Philmont swell only a little. Though not very exciting to look at, these beds have an exciting history; for they are not simply muds swept into the ocean by streams wearing down the lands but are the remains of volcanic ash that blew into the sea from eruptions of distant volcanoes and mixed with other fragments settling to the bottom. Still visible under the microscope are the outlines of the original fragments of delicate volcanic glass, now changed to clay (fig. 29). The same dark shale formation has been traced over more than half

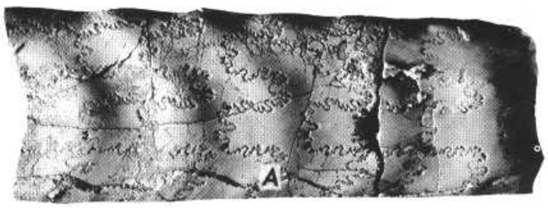
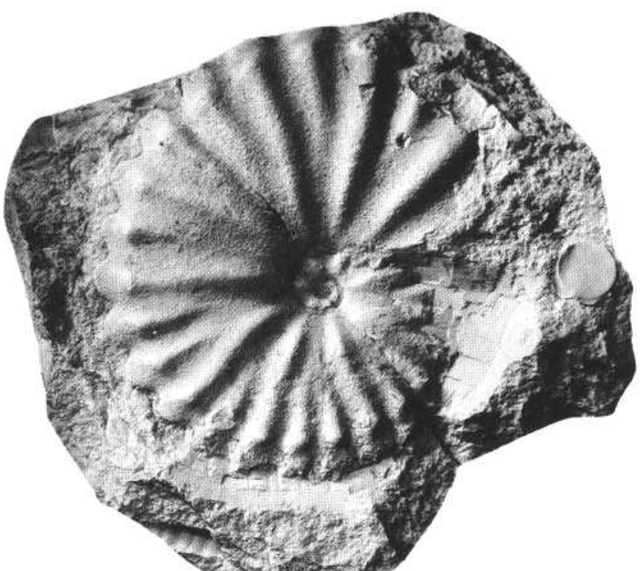


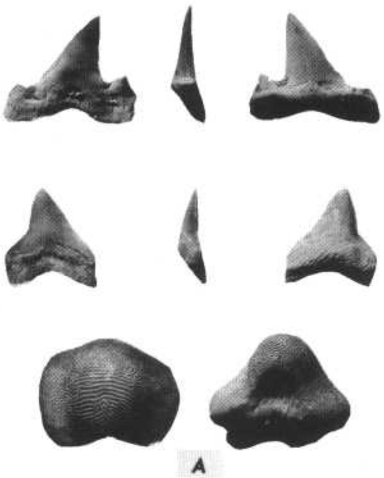
BLACK SHALE (Graneros Shale)—once it was mud on the floor of the sea. A, Bank of lower Urraca Creek. Light layers are limestone. B, Piece of shale, natural size. C, Slice of shale, magnified 30 times. This slice is cut across bedding and reveals the edges of three paper thin layers. The dull gray material is clay. The dark streaks are the edges of mica flakes and of plant remains. Bright sharp-edged grains are quartz. A few round white grains are fossil organisms called coccoliths. (Fig. 25)

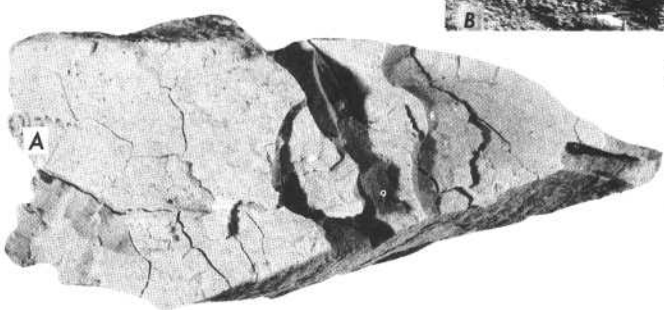



FOSSILS FROM BLACK SHALE—their descendants live in the ocean today. A, Oyster bed. B, Clam. (Fig. 26)

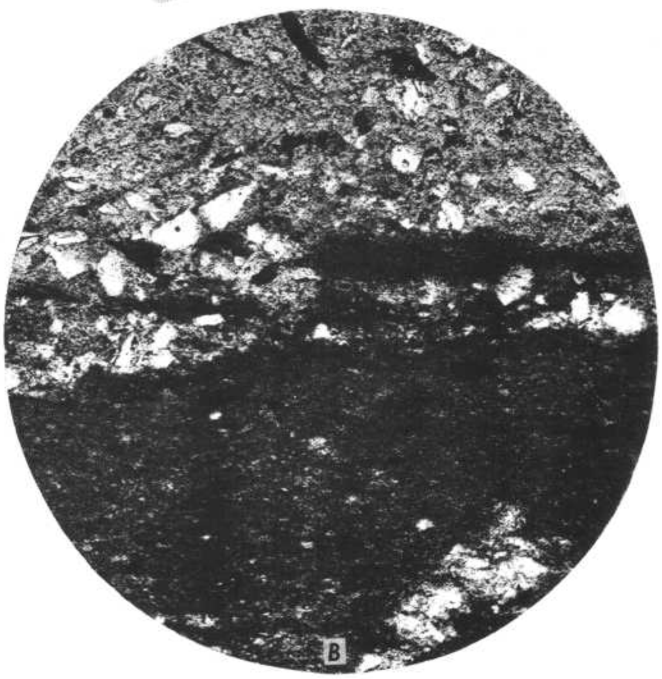
FOSSILS FROM BLACK SHALE: ammonites, extinct relatives of cuttlefish and squids. (Fig. 27)

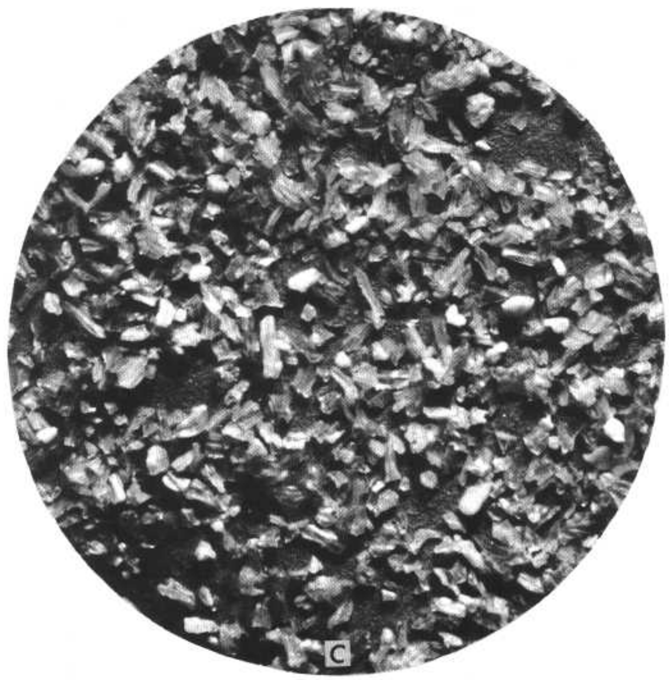



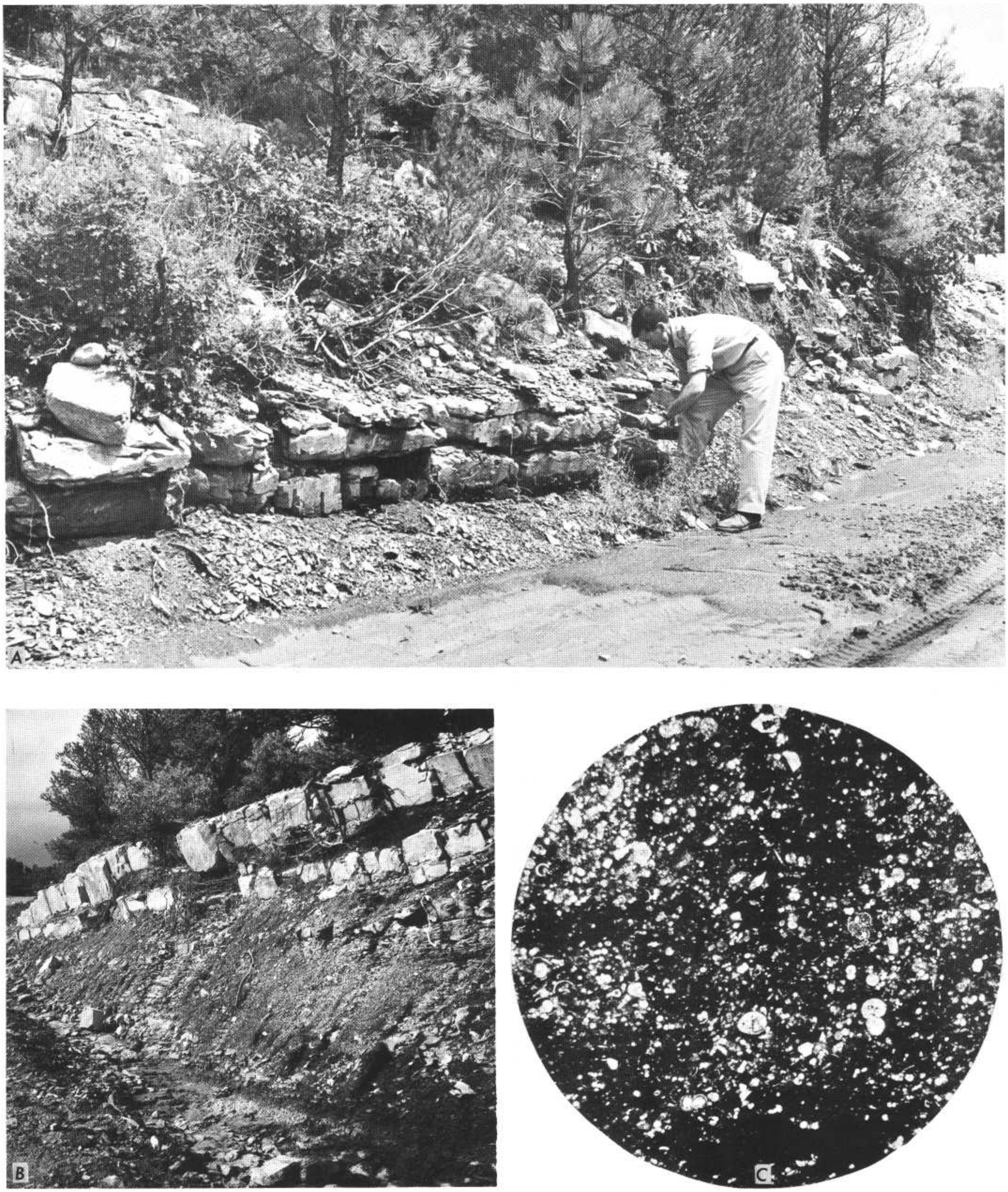


FOSSILS FROM BLACK SHALE (Pierre Shale): A, Shark teeth. Sharks have no bones. Instead, they have skeletons of soft cartilage, so only their teeth and, rarely, their fins are found as fossils. B, Fossils are often found in pods of limestone like this one, which is surrounded by shale. (Fig. 28)





ORANGE SHALE (from Pierre Shale). A, Piece of orange shale that swells when wetted because it contains altered volcanic ash. Natural size. B, Slice of shale containing much volcanic ash, now changed to clay; origin of ash revealed under the microscope by the shapes of its grains. Magnified 16 times. C, Unaltered pure volcanic ash from Montana magnified 5 times for comparison. (Fig. 29)



LIMESTONE—another kind of hardened mud (Fort Hays Limestone Member). A, On South Fork Urraca Creek. B, At entrance to New Abreu Base Camp. Dark layers are shale. C, Slice of limestone, magnified 24 times. Nearly all the white grains are calcite; sharp-cornered ones are crystals, round ones are fossils. A few rounded white grains are quartz. The gray areas are clay, plant debris, and a little mica. (Fig. 30) a million square miles in the interior United States and Canada. Everywhere, it has beds of altered ash like these. Thin as they are, they add up to many cubic miles of volcanic dust and tell of tremendous eruptions somewhere to the west. The volcanoes themselves, however, no longer stand, and nó remains of them have yet been found.

Gray limestone

Tan- or white-coated low ledges of gray limestone rise gently above the sand-gravel blanket in the plains south of Philmont Ranch Headquarters and stand out on the sides of several benches. Limestone can easily be seen along the north side of the trail along South Fork Urraca Creek above the turnoff to Stone Wall Pass (fig. 30*A*) and on the Rayado Creek Trail at the entrance to New Abreu Base Camp (fig. 30*B*). The rock, in beds a foot or two thick, seems very hard and tough, but it is readily broken with a hammer and easily scratched with any knife blade. Like the shale that is interbedded with it, the limestone is very fine grained. Through a microscope, the limestone is seen to be composed mainly of tiny grains of calcite surrounded by the same materials that are common in the dark shale—clay, mica, quartz, and organic debris (fig. 30*C*). (The limestone specimen in fig. 30*C* is very impure; other parts of the same layer are practically pure calcite in tightly packed crystals and pellets.) Here and there, as in the shale, are fossilized remains of oysters, clams, snails, and ammonites.

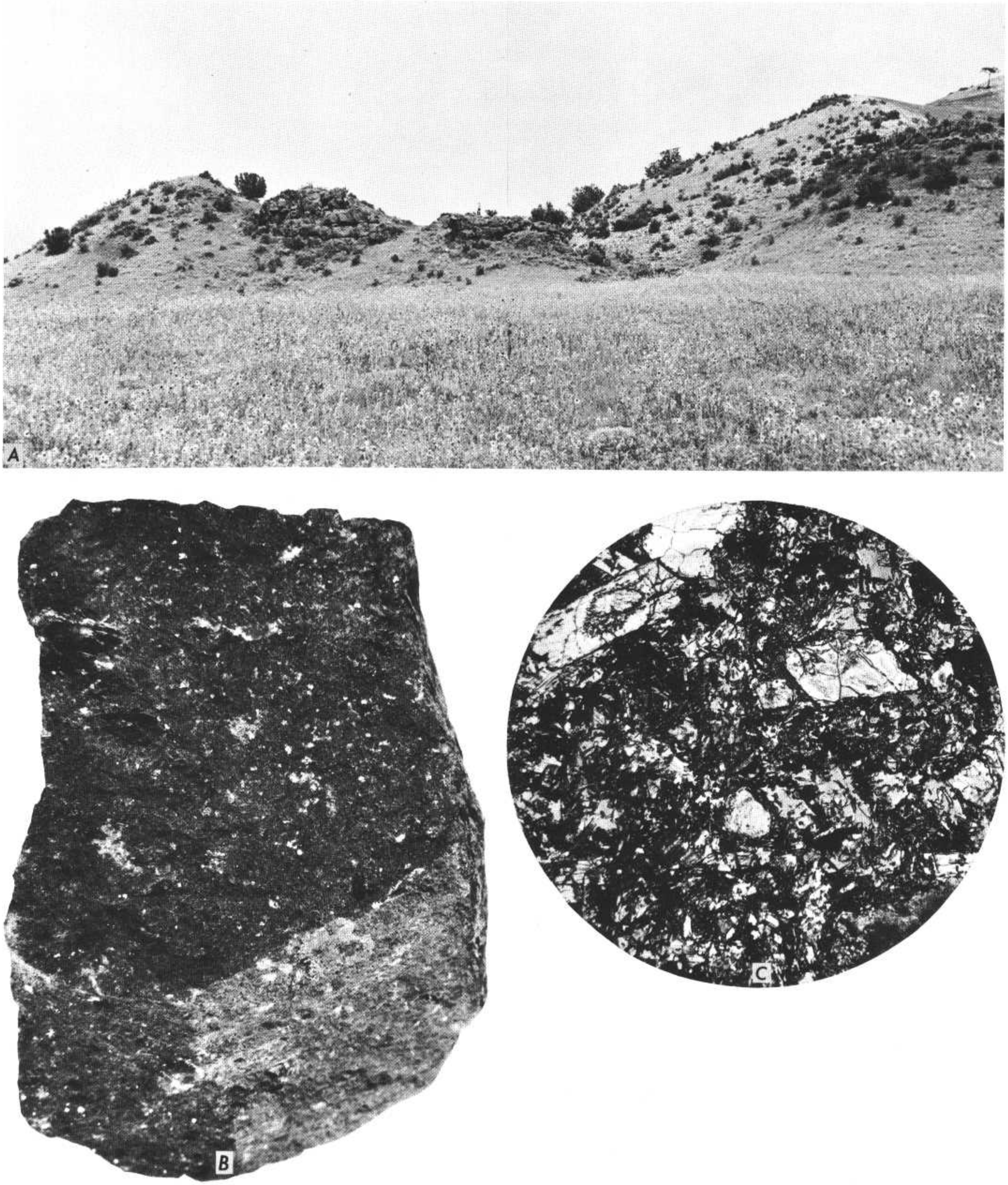
The limestone must have formed in somewhat the same way as did the shale—that is, as a sediment on the sea floor. But the calcite, unlike the clay, mica, and quartz, is not bits of older rocks washed in from the land. Calcite (calcium carbonate) is soft and is much more soluble than other common minerals in ordinary surface water (dissolved calcite is the main cause of "hard" water). Limestone does not, therefore, survive much stream transport or wave washing. So the calcite particles must have formed by some sort of chemical action not far from where they are now. Where inflowing streams and the activity of marine life supplied more calcium carbonate than the sea water could keep dissolved, some of the calcium carbonate was precipitated as crystals or as droplike groups of minute crystals to make a kind of calcite mud. Part of the calcium carbonate also went into the bodies of plants and animals, and fragments of these also sank into the mud. Later, the mud was buried by other sediments and was dried and compressed by their weight into limestone.

Limestone muds that may some day become rocks like these are forming in many parts of the ocean, where they are not diluted by too much debris from the lands—for example, in the shallow water on the Bahama banks, in the Pacific coral islands, and also at many places on the deeper ocean floor.

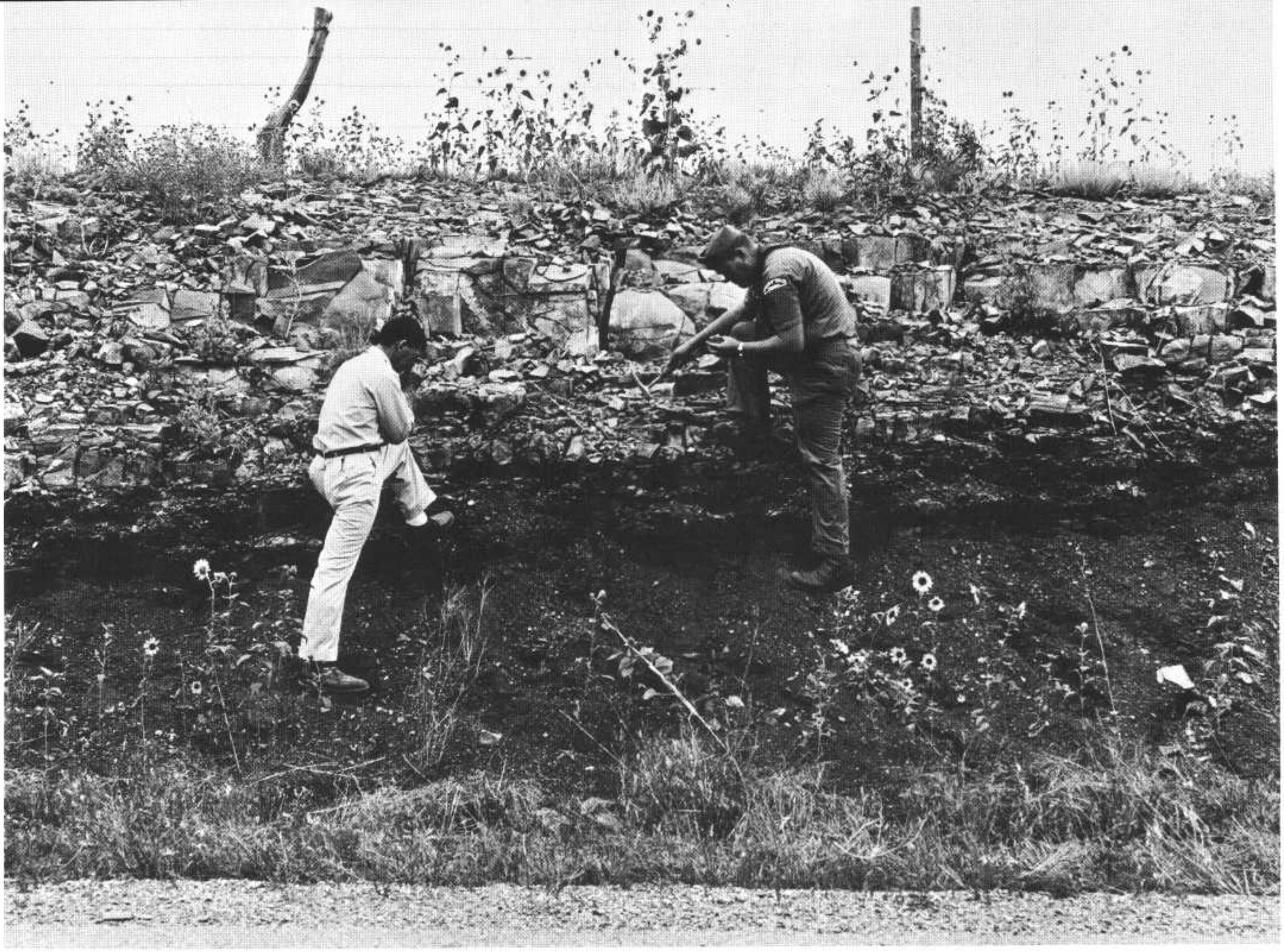
Dark mica-rich lamprophyre

Lamprophyre, a rare rock the world over, is fairly common on the plains of Philmont. It is best seen at the southern edge of Horse Ridge, 1.2 miles northwest of Scout Ranch Headquarters on the north side of the trail to Cimarroncito Base Camp (fig. 31). The lamprophyre in Horse Ridge is a coarse-grained greenish- to brownish-black rock that looks like it is made wholly of closely packed flakes of glittering brown biotite mica (fig. 31). Through a microscope, however, it can be seen that the rock actually is less than half biotite—part of it in large crystals, and part in small crystals—and that the rest is mostly small crystals of green pyroxene intergrown with the biotite and with a little magnetite and calcite (fig. 31). The grains of these minerals are not rounded, as they would be if they had been washed in by water, but have the sharp corners and edges of crystals. Packed tightly together, they look as though they all grew at about the same time, although the large biotite crystals may have had a head start. Besides having crystals instead of rounded grains, this rock contains no quartz or clay or organic remains like the surrounding shale or the limestone does. Furthermore, it is not layered in the shale but is a vertical sheet 6 to 8 feet thick that cuts across the bedding (see figs. 110, 116).

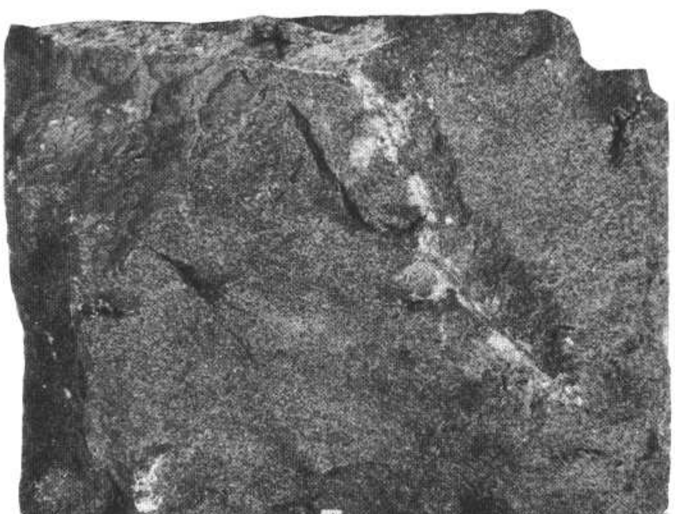
The lamprophyre is not a sedimentary rock that settled out of running or standing water. Instead, it rose as a thick hot melt from inside the earth and oozed into fractures in the already solid shale. Upon cooling, it crystallized like fudge or sugar. The blocks that show so well in figure 31*A* are the result of shrinkage due to cooling. Rocks of this sort, which cooled from a melt, or magma, are called igneous rocks. A very large part of the rocks at Philmont formed from the freezing of rock melts, but most of them are very unlike the lamprophrye in appearance and in mineral content. Most of them, however, are like the lamprophyre in having two generations of minerals—an earlier formed set of large crystals, called phenocrysts, held in a later formed base of smaller crystals or of glass, which is molten rock that cooled so quickly that no crystals had time to form. An igneous

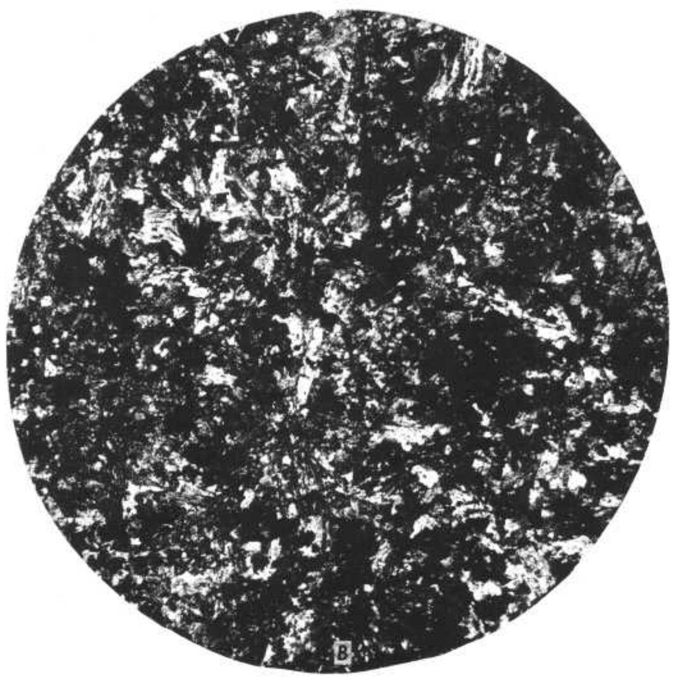


LAMPROPHYRE. Molten material—magma—from within the earth rose in cracks and froze slowly to make this rare biotite-pyroxene rock. A, Ridge of lamprophyre at Horse Ridge. B, Piece of lamprophyre, natural size. C, Slice of lamprophyre, magnified 24 times. Large crystals of biotite surrounded by intergrown small rods of pyroxene and bright flakes of biotite, and scattered light patches of calcite and black grains of magnetite. (Fig. 31)

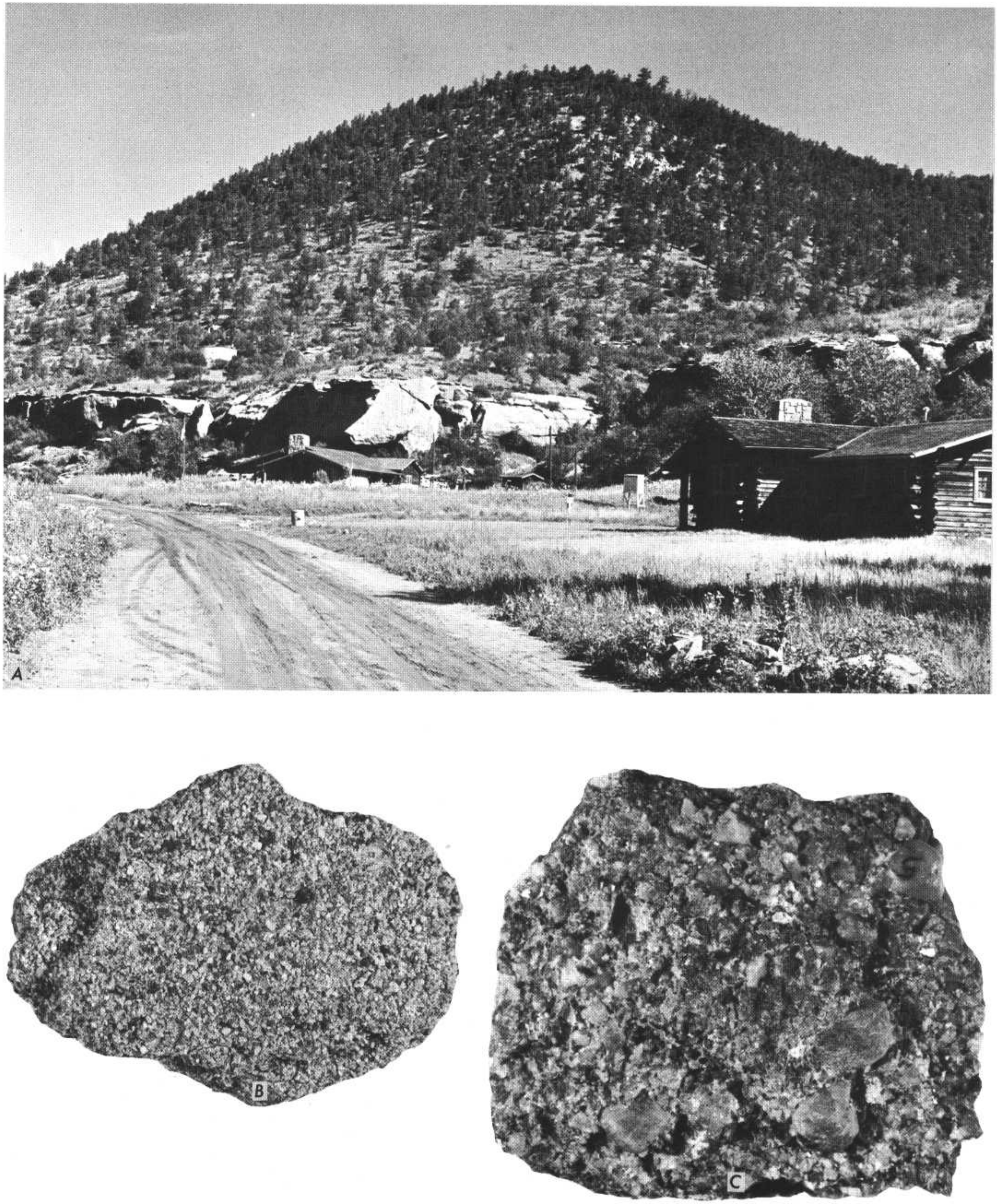


LIGHT-COLORED ANDESITE IN DARK SHALE (Pierre Shale) on State Highway 21. (Fig. 32)





A CLOSER LOOK AT ANDESITE. A, Piece of andesite, natural size. B, Slice of andesite, magnified 24 times. The rock is made mainly of microscopic lath-shaped crystals of glassy plagioclase feldspar and flakes of brown biotite but contains many grains of transparent calcite and a little black magnetite. (Fig. 33)



YELLOW SANDSTONE AND CONGLOMERATE (Poison Canyon Formation), deposited by ancient streams. A, Outcrops at Ponil Base Camp. B, Piece of yellow sandstone. C, Piece of yellow conglomerate. (Fig. 34) rock that is more than half phenocrysts is called a porphyry; if phenocrysts are common but less than half, the rock is merely porphyritic. The lamprophyre is, therefore, porphyritic, though at first glance it seems to be a porphyry.

Other sheets of lamprophyre, some cutting across the bedding, some parallel to it, makes less striking outcrops in the terraces 2 miles east of Ranch Headquarters. In some of these the rock is much finer grained than the rock at Horse Ridge and looks like limestone, except for the glitter of tiny biotite flakes; some even reacts to hydrochloric acid like limestone, by fizzing vigorously, because it contains much calcite.

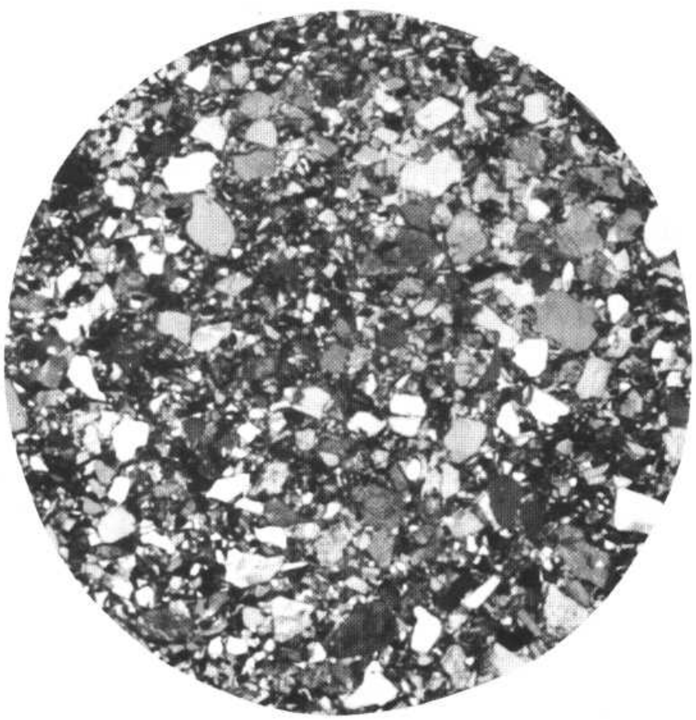
Brown andesite

Andesite, though rare in the lowland plains, is worth mentioning because it is easy to see on State Highway 21 at the rise 0.8 mile north of Ranch Headquarters (figs. 32, 33). Here it makes a sheet about 10 feet thick parallel to the bedding of black shale. The shale is hardened and splintery for several inches above and below the andesite sheet.

The andesite is a dense hard fine-grained rusty-brown rock containing scattered pale-blue spots and streaks (fig. 33*A*). The rock is made mainly of microscopic lath-shaped crystals of glassy plagioclase feldspar and flakes of brown biotite but contains many grains of transparent calcite and a little black magnetite (fig. 33*B*). The blue material is opal. In weathering, the black magnetite rusts to brown hematite, which gives the rock its color.

Like the lamprophyre, the andesite rose from below as a melt and froze in the shale. The heat released by the cooling andesite dried and baked the shale, making it brittle along the contact. The shale for a foot or so both above and below the andesite sheet is baked and brittle (the sheet must be followed eastward to learn this, for its top is not exposed in the roadcut), proving that the andesite actually squeezed between the shale layers instead of flowing on the surface like lava. A surface flow would alter the rocks it flows over but could not affect layers not yet deposited on its top.

The molten andesite was certainly hot enough to do a lot of baking. Laboratory experiments with rocks like andesite show that they melt completely at about 2000° F at near-surface pressure (so does ordinary window glass) and are completely crystallized by the time they cool to 1800° F. The lamprophyre melt, having more water to keep it fluid, may not have been quite so hot.



SLICE OF YELLOW SANDSTONE, magnified 16 times. Grains are mostly quartz and feldspar. (Fig. 35)

Rocks of the benchlands

The rocks that underlie the benchlands are not much like those beneath the plains, but the rocks of the two areas have two things in common—they are mostly made of fragments of older rocks deposited by streams or in the ocean, and they lie for the most part in nearly horizontal layers, roughly parallel to the bench surfaces. The benchlands also have some igneous rocks, but these rocks are mostly very different from the igneous rocks of the plains.

Yellow sandstone and conglomerate

In the striped benchlands that make up most of the north half of Philmont, the light-colored stripes are mainly yellow sandstone and conglomerate. These rocks cap the benches on both sides of Cimarron Creek. Dipping gently northward, they come to creek level in the northern part of the area, as in the outcrops near Ponil Base Camp (fig. 34). The sandstone is made mostly of poorly rounded grains of glassy quartz and cloudy feldspar but contains angular bits of biotite, hornblende, and dark shale (fig. 35). The grains, which vary widely in size, are loosely held together by a little clay and calcite cement. Open spaces between grains amount to as much as a fourth of the total volume of the rock.

Except for the cement, this rock is just like the sand on the banks of the present creeks and no doubt started out in much the same way. As do the streams of today, the streams that deposited the sediments which made these rocks dried up sometimes and also shifted their courses often, leaving the soft wet sand to dry in the sun. Cracks caused by drying are still preserved on the surfaces of some sandstone beds at Philmont, as figure 36 shows. The slab pictured, more than 20 feet long, fell off a hill. The cracked surface, now vertical, was originally flat and was the bottom of a layer that was deposited on top of a layer that had dried, cracked, and hardened. It is, then, a print or mold of a sun-cracked surface rather than the surface itself. The shape of the plates between the cracks shows why: mud-dried plates curl up at the edges and are cup-shaped, but the plates on the sandstone surface are higher in the center—dome shaped—so they are molds.

Another result of shifting stream courses is crude crossbedding, shown in figure 37. The beds from creek level to twice as high as the man's head dip gently to the right. Above this level they are cut off by flatter beds. The lower beds once extended farther but were planed off by a flood. Then, the receding flood waters, or a later flood, dropped new sand on the scoured surface.

Trapped with the sand were fragments of trees and other plants that have been preserved as fossils (fig. 38). (The fossils in the photographs come from elsewhere, but similar ones have been found at Philmont.) Plants like this grow only on land; so rocks containing abundant remains of land plants and no recognizable signs of ocean life surely were deposited on land. Later, the sand was covered by other rocks and was cemented with material deposited in part from water buried with the sand and in part from new water that percolated down.

Yellow conglomerate (fig. 39) made of pebbles and larger chunks of older rocks cemented together crops out near the yellow sandstone. The sandstone and conglomerate grade into each other and are interbedded (fig. 40): the conglomerate is simply a king-size sandstone. Older rocks that could have supplied the fragments in the sandstone crop out, as we shall see, only in the core of the Cimarron Range to the southwest and in the Sangre de Cristo Mountains still farther west. If the sandstone is cemented river sand, the conglomerate is cemented river gravel. Both were probably deposited by streams that flowed from the west, like those of today.

Light-gray sandstone

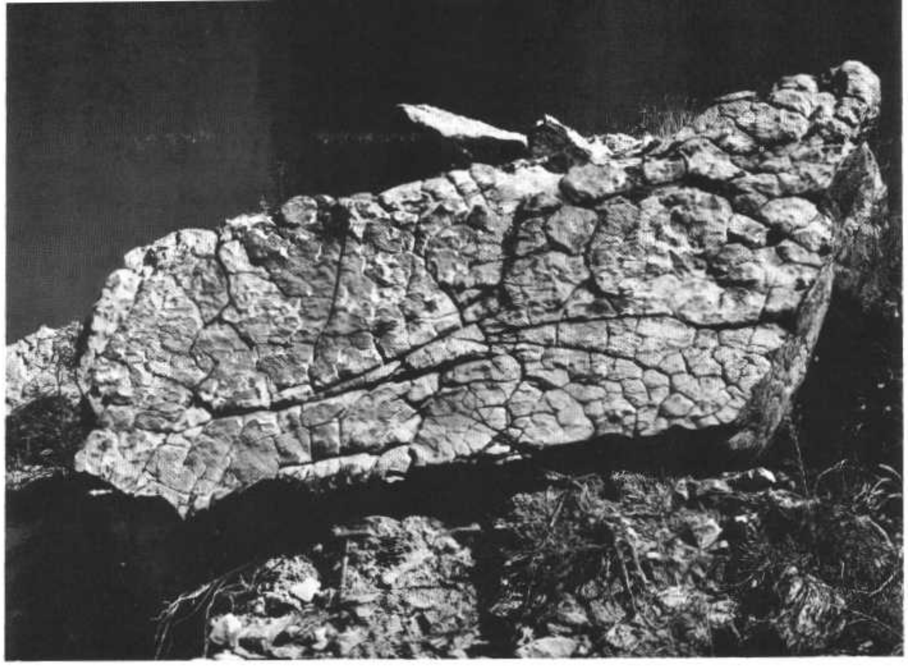
A different kind of sandstone crops out in sheer low cliffs near the base of the benches flanking lower Cimarron Creek and lower Ponil Creek (fig. 41). This sandstone, which is broken into huge blocks by widely spaced joints, is light gray and is made up mostly of quartz grains and only a very small amount of feldspar, biotite, and hornblende (fig. 42). Unlike the yellow sandstone, its grains are nearly all about the same size, the quartz and feldspar grains are somewhat rounded, and there are no shale chips (fig. 42*B*). Like the yellow sandstone, this rock contains a few plant fossils (fig. 43) and also some odd knobby tubular masses, called *Halymenites*, made by some sort of burrowing animal or branching plant that once lived there (fig. 44). (The plants and tubes in the photographs were collected from this sandstone northeast of Philmont.) These masses used to be called fossil seaweed, but now we are not so sure just what kind of organism they represent. They look very much like the burrows of living crabs in Atlantic coast sand beaches.

This rock was probably deposited on an ocean beach. Its sand must have been washed and rewashed many times to produce the even size and slight rounding of the grains. This kind of working over is common on ocean beaches, as are burrows and also leaves, blown from near-shore trees.

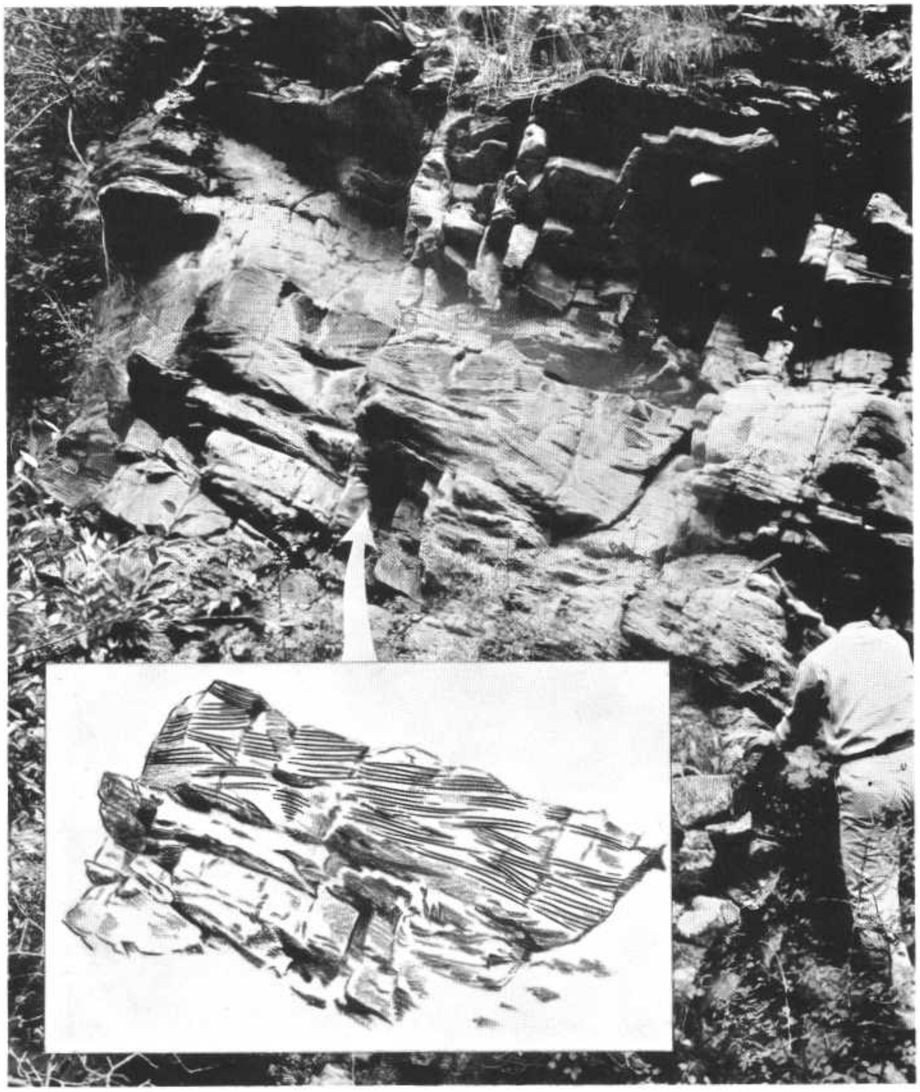
Shale

Black marine shale like that beneath the plains is also a major rock type in the lower parts of the benchlands. The soft shale rarely makes ledges itself, but it can be seen in many places where it is protected by overlying ledges of sandstone, as along the north side of Highway 64 west of Cimarron town from Slate Hill to Turkey Creek (see right edge of fig. 3) and at the heads of a few streams on the flanks of Urraca Mesa (fig. 45).

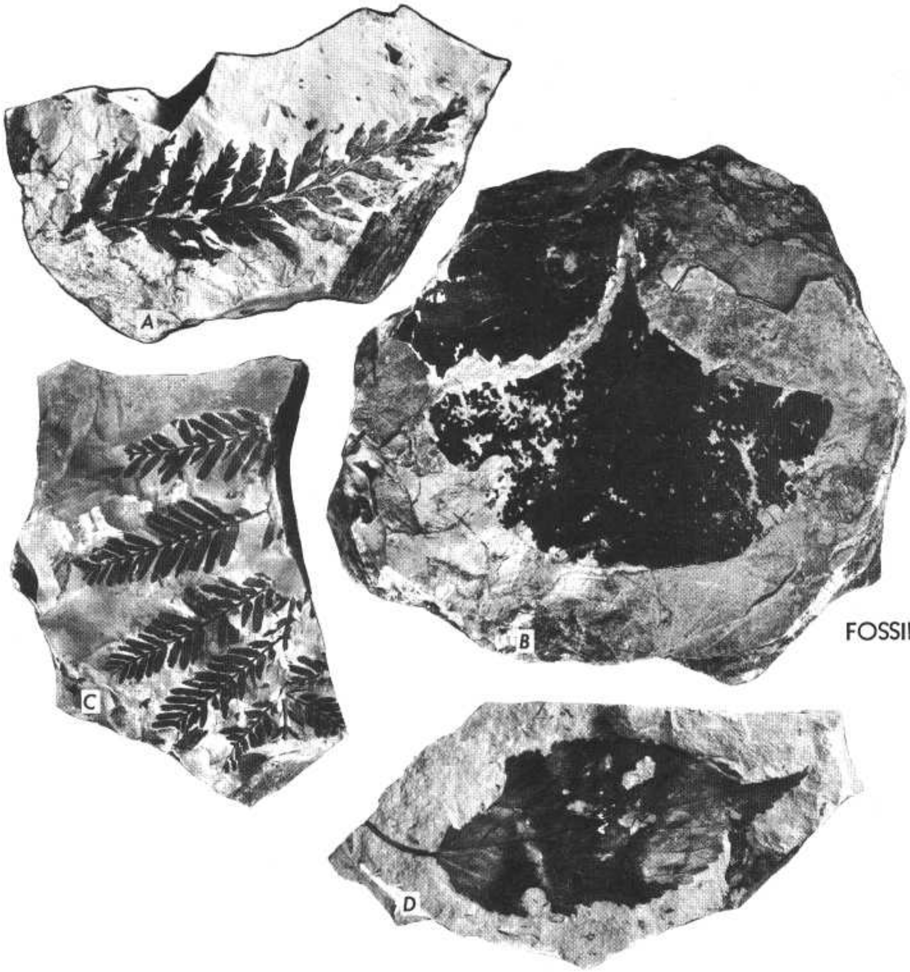
Shale that is lighter colored and sandier than the black shale makes most of the dark stripes in the striped benchlands. Like the black shale, it rarely crops out but is covered with soil and slide rock. The sand in this shale is just like that in the yellow sandstone and conglomerate, and so



YELLOW SANDSTONE (Raton Formation) that has fossil sun cracks, Ponil Creek. (Fig. 36)

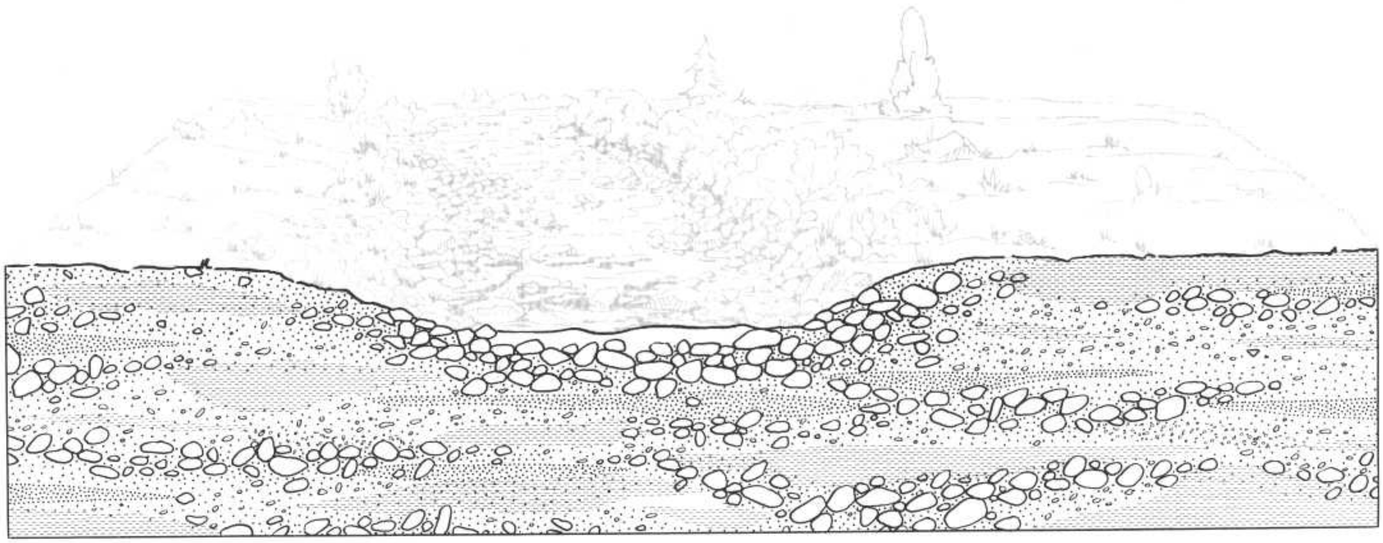


CROSSBEDDING in yellow sandstone (Raton Formation), Ponil Creek. A result of shifting stream channels. (Fig. 37)



FOSSIL PLANTS from ancient stream beds. (Fig. 38)

YELLOW CONGLOMERATE (Poison Canyon Formation) in high benchlands north of Baldy Mountatn. (Fig. 39)



SANDSTONE, CONGLOMERATE, AND SHALE in old stream deposits, showing grading (gradual change) and bedding (sharp change). (Fig. 40)

LIGHT-GRAY SANDSTONE (Trinidad Sandstone)—relic of a vanished ocean beach. Outcrop on lower Ponil Creek. (Fig. 41)

are the fossils—bits of land plants. Also, in places the shale grades into yellow sandstone in the same way that the sandstone grades into conglomerate (see fig. 41). This shale was not deposited in the sea, like the black shale, but by streams on land, like the yellow sandstone and conglomerate. When the streams flooded, they left sand and gravel in their channels but carried mud as far as the water spread, finally dumping it on the flood plain, where it was mixed with debris from plants that had lived and died there. Eventually this soupy mixture was buried by deposits from later floods, the water was mostly squeezed out, and it became rock.

Dark basalt

Basalt, in dark hues of gray and green, caps the mesas in the southwestern part of Philmont. The best exposures are at the mesa edges (see fig. 45); elsewhere, the basalt is concealed by a thin but continuous cover of soil and rubble. From a distance the basalt seems to be broken into neat vertical pencil-like columns, but close up this pattern disappears (fig. 46); for the rock has many fractures besides the vertical joints that make the columns, and it tends to break down into piles of jagged rubble. Most of the rock is dense and glassy, but it has a few green-brown greasy-looking phenocrysts of olivine and scattered football-shaped holes (fig. 47*A*). In places the rock has many of these holes and approaches pumice. Some of the holes are filled with white calcite, and a few others with white fibers of zeolite (fig. 47*B*). Using a microscope, we see that the large olivine phenocrysts "float" in a mixture of brown glass and tiny crystals of colorless feldspar, green pyroxene, and golden olivine (fig. 47*C*).

This rock flowed out on the surface as a thick glowing-hot paste. It is in every way like the lavas that are erupted every few years by Mauna Loa and Kilauea volcanoes on Hawaii. The large crystals probably formed while the melt was still deep within the earth, and the smaller ones as it was rising through fissures, or perhaps even as the lava cooled on the surface. Most of the rock cooled so rapidly at the low temperature and pressure of the atmosphere that no crystals formed, only glass. Most of it, too, had little gas and cooled to a dense rock like that in figure 47*A*. The basalt that now has bubble holes originated miles below the earth's surface, and there it contained several percent of dissolved gases—mostly water vapor—which were kept dissolved by the pressure of the overlying rocks. As the basalt rose and the rock pressure grew less, the gases expanded and formed bubbles. If the gas in a bubble escaped while the lava was still hot enough to flow, the hole simply closed up; but if the rock was fairly hard before the gas escaped, the walls of the bubble remained. Later, hot water related to the eruption, or cold water percolating from the surface, deposited white calcite and zeolite minerals in these open spaces and completed the formation of rocks like that in figure 47*B*.

As the basalt cooled, it cracked and shrank, and vertical joint columns and cross cracks were formed. The basalt, to judge by what we know happens at Hawaii, emerged from the volcano white-hot at a temperature of nearly 2000° F. Most of the basalt at Philmont seems to have come from volcanoes to the south, but the lava on Fowler and Urraca Mesas probably came from a vent at the mountain front, near Crater Peak.

Dacite porphyry

Dacite porphyry, though rare in the benchlands compared to sandstone, shale, and basalt, makes some striking light-colored outcrops in the northwestern part of Philmont. It caps Wilson Mesa, on South Ponil Creek, and makes ledges near the rims of the benches bordering Middle Ponil Creek and its tributaries above Ponil Base Camp (fig. 48). These exposures are all parts of a single nearly flat sheet no more than 100 feet thick but at least 5 miles long, that lies parallel to the bedding of the surrounding sandstones and conglomerate. The sandstone above has been eroded in many places, leaving the resistant dacite porphyry as the bench capping, as in figure 48*A*. In other places, such as in Bonita Canyon, the sheet is sandwiched between beds of sandstone. The dacite outcrops are about the same color as the sandstone but have vertical jointing like the basalt; thus, they are easy to identify, even from a distance.

The dacite, though different from the lamprophyre and basalt in many ways, is made of interlocking crystals (fig. 48*B*) and, like them, is an igneous rock. The dacite is a porphyry because it has many large crystals in a mosaic of tiny ones. As dacite porphyry is rather rare in the benchlands but is the most prominent ledge maker in the mountains, we will say more about its composition and origin later. The dacite has slightly baked and discolored the sandstone both below and above, showing that it was squeezed in between the sandstone beds, like the andesite near Highway 21, and did not flow out on the ground, like the basalt.

A CLOSER LOOK AT BEACH SANDSTONE. A, Piece of sandstone. B, Slice of sandstone, magnified 24 times; doubly polarized light. Because of double polarization, grains of the same mineral may be shaded in all tones of white to black. Most of the grains are of clear quartz; a few lined or striped ones are feldspar, biotite, or hornblende. Bright rims on some grains are clay and calcite. (Fig. 42)

Andesite

Some thin sheets of salt-and-pepper andesite and andesite porphyry (andesite that has many large crystals of feldspar) make striking ridges that can be traced for miles in the northwest corner of Philmont. Nearly all are vertical, like the lamprophyre of Horse Ridge, but a few are nearly flat, like the dacite porphyry of Wilson Mesa. Because all the andesite sheets in the benchlands are hard to reach or are in mining areas closed to visitors, no more will be said of them.

Coal

Shiny-black coal is a fairly common rock along the southern edge of the northern benchlands, from the north side of Cimarron Creek, below Ute Valley, to the north side of Ponil Creek, below Chase Canyon. Beds of coal as much as 4 feet thick are interlayered with shale and sandstone. The coal, however, rarely crops out, because it falls to pieces on exposure to air. A little coal was once mined here, and countless chips of disintegrated coal can be seen on waste-rock dumps at the openings of abandoned mines on the slopes of Slate Hill (see fig. 79) and on lower Ponil Creek (fig. 49). It is interesting to see the coal and other rock debris on the dumps, but it is unwise to enter the mines. They were dangerous when mining was still going on and are much more so now, after decades of neglect.

Coal, when magnified enough (fig. 50), is seen to be made mostly of altered and compressed plant fragments. Such material accumulates in swamps and becomes peat, an early stage product in the coal-forming process. There are many present-day peat bogs. Plants are made almost wholly of compounds of carbon, oxygen, and

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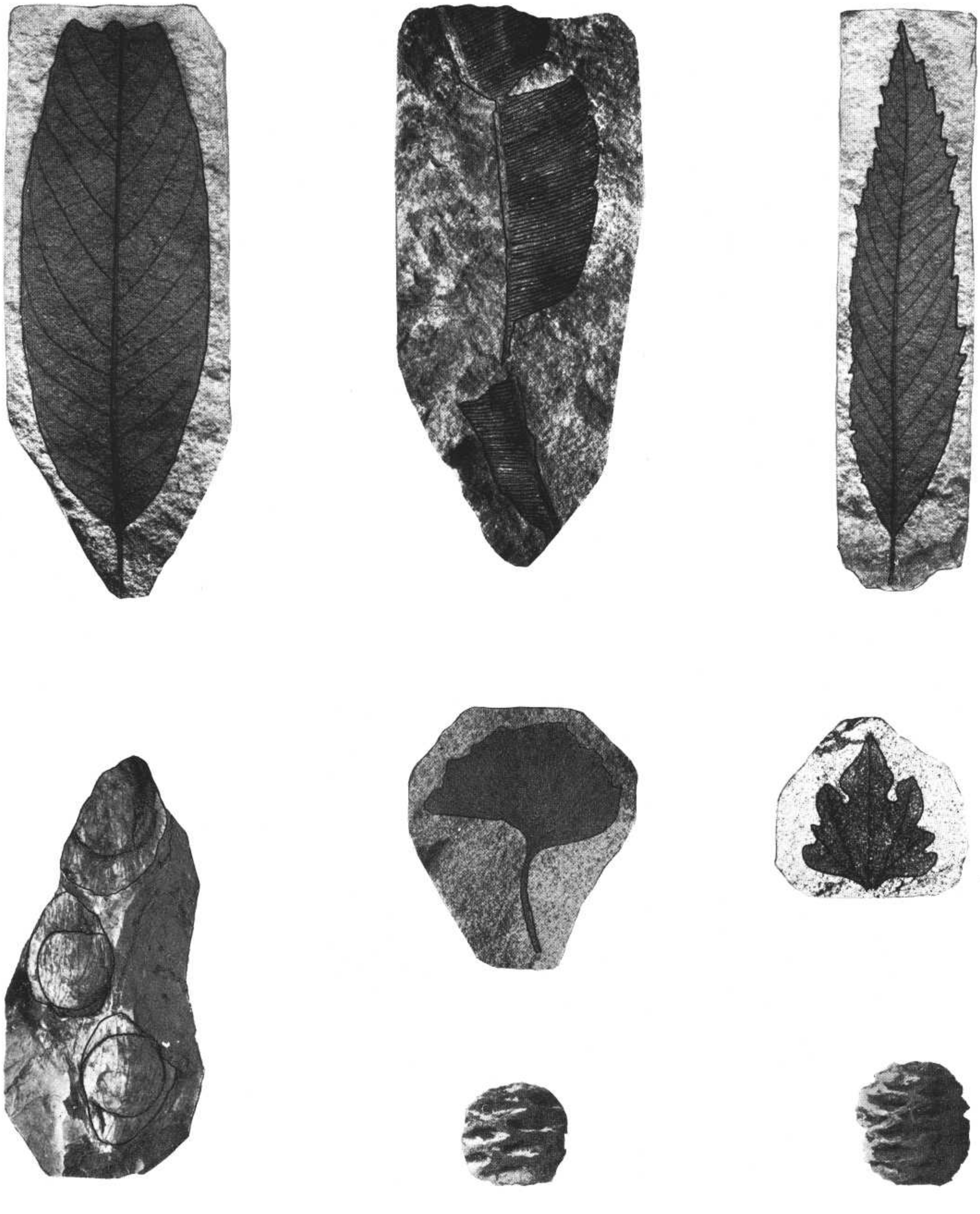
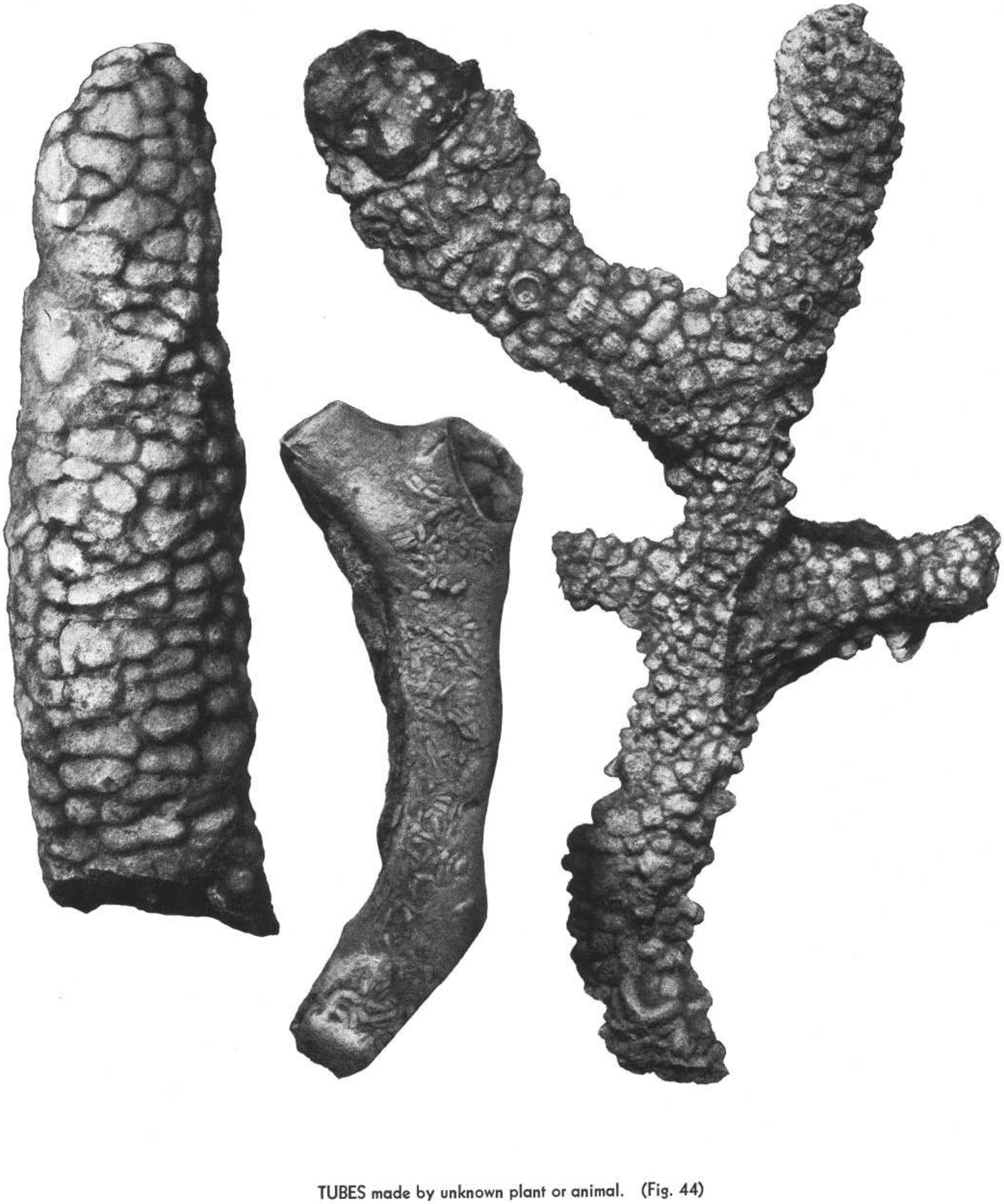
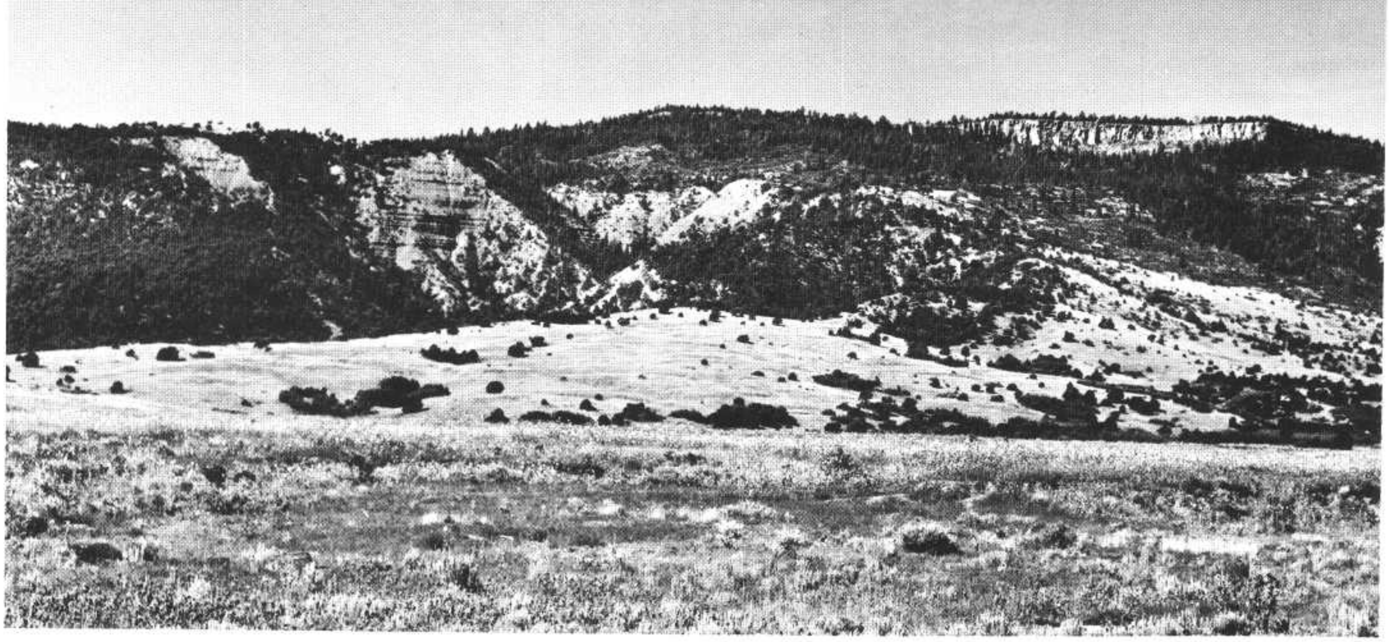


PLANT FOSSILS: leaves, cones, and nuts. (Fig. 43)

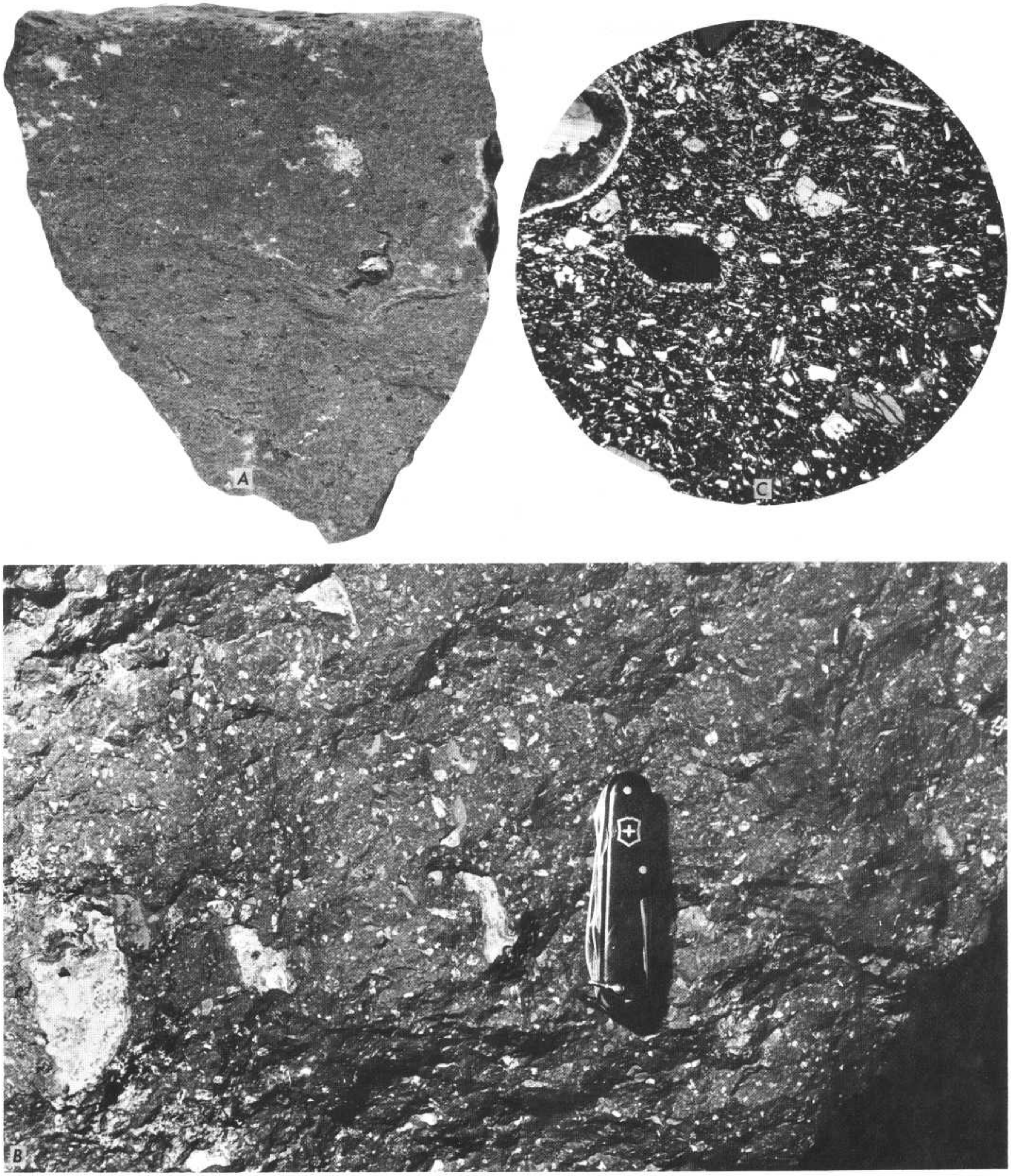


TUBES made by unknown plant or animal. (Fig. 44)

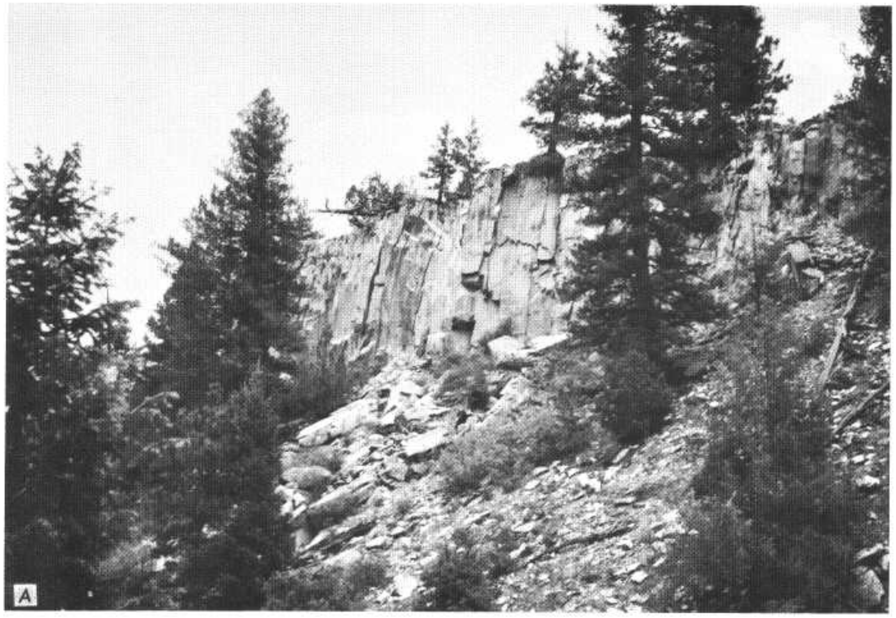


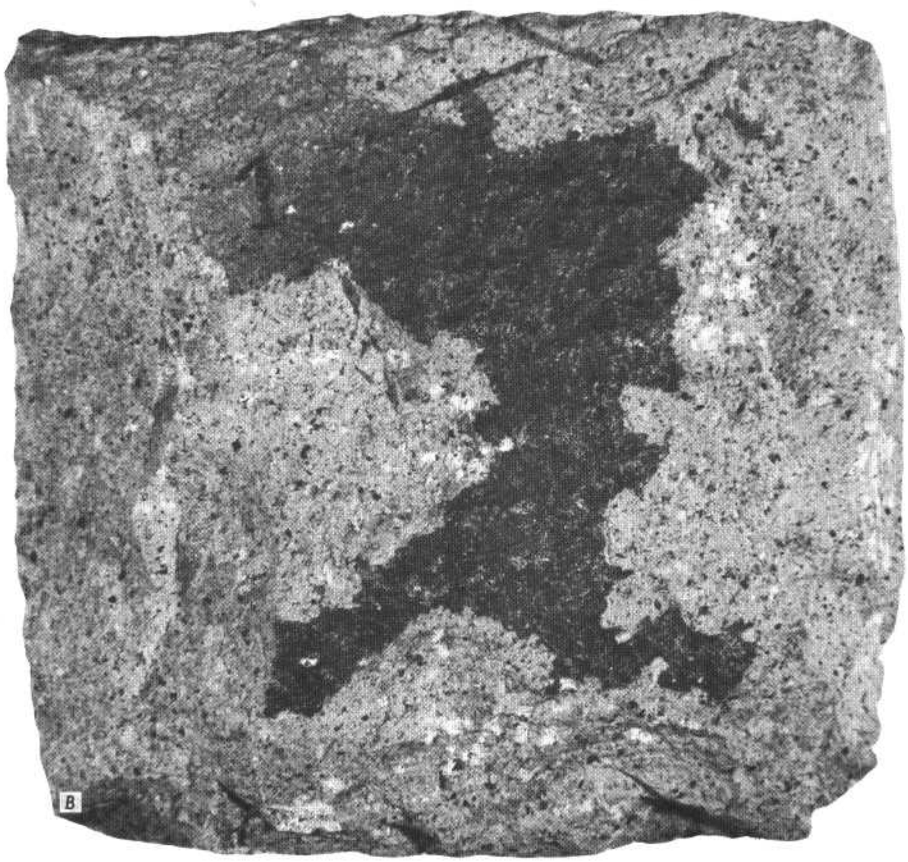
BLACK SHALE AND BASALT in the benchlands. East side of Urraca Mesa seen from State Highway 21. Layered rocks (left rear) are black shale (Pierre Shale). Except for the mesa cap, all the high ground in the view is underlain by shale, mostly covered by soil, trees, slopewash, and landslides. The mesa capping, of hard rock that has many vertical cracks (right rear), is basalt lava, poured out from a volcano that is now extinct. (Fig. 45)

BASALT RUBBLE on Urraca Mesa. (Fig. 46)



A CLOSER LOOK AT BASALT. A, Piece of dense basalt, natural size. B, Basalt that has many bubble holes, now filled by calcite and zeolite; half size. C, Slice of basalt, magnified 8 times. Large crystals of olivine with corroded edges (upper left) "floating" in a mixture of glass (dark gray) and tiny crystals of feldspar, pyroxene, and olivine. Large black area is a hole where a crystal was pulled out of the rock slice during grinding. Doubly polarized light. (Fig. 47)



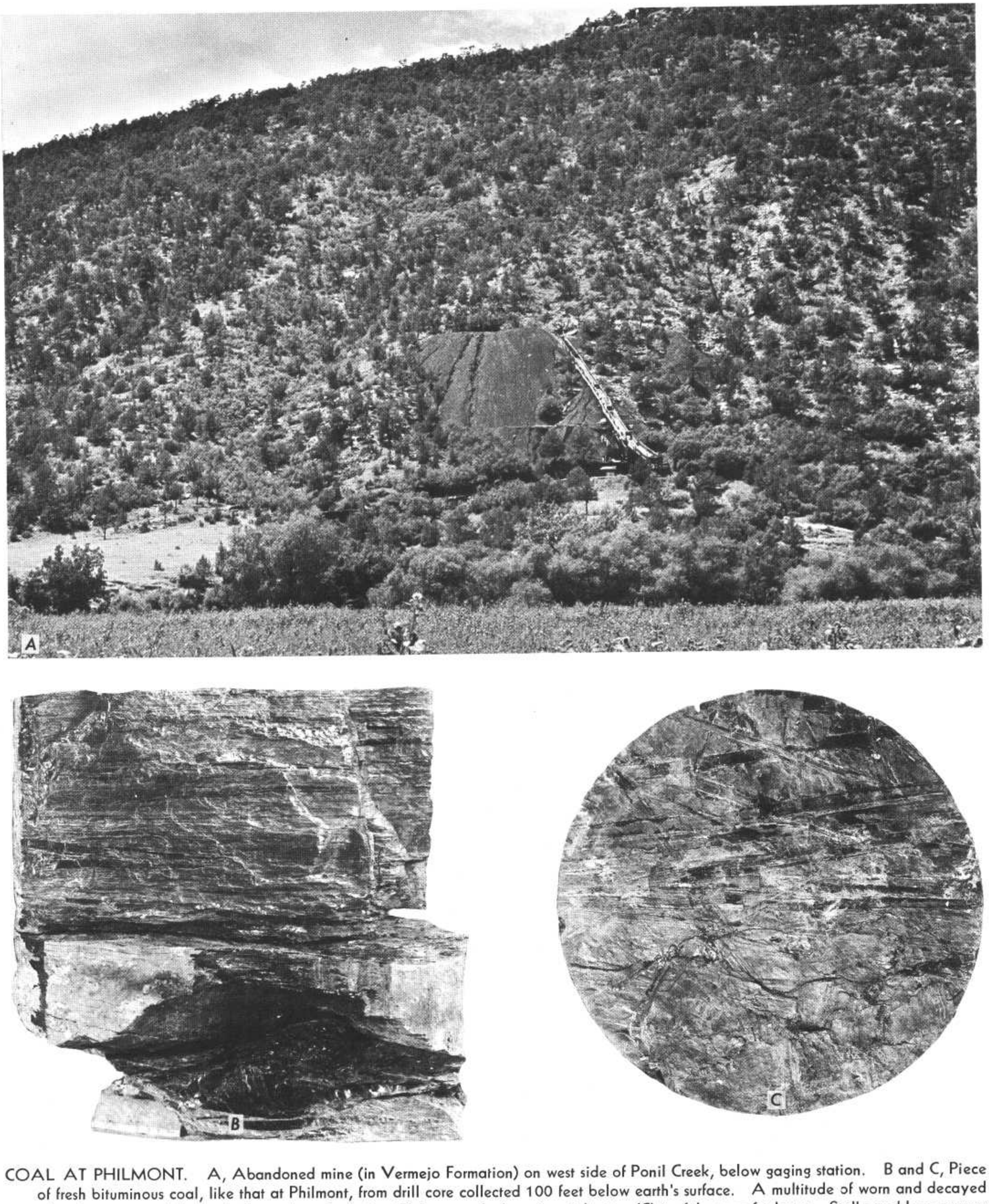


DACITE PORPHYRY. A, Outcrop of a sheet of light-colored dacite porphyry near Dan Beard Trail Camp. The cliff is the edge of the sheet. Beneath, covered by dacite porphyry rubble, is sandstone. B, Specimen. The dark stains are the result of weathering. (Fig. 48)

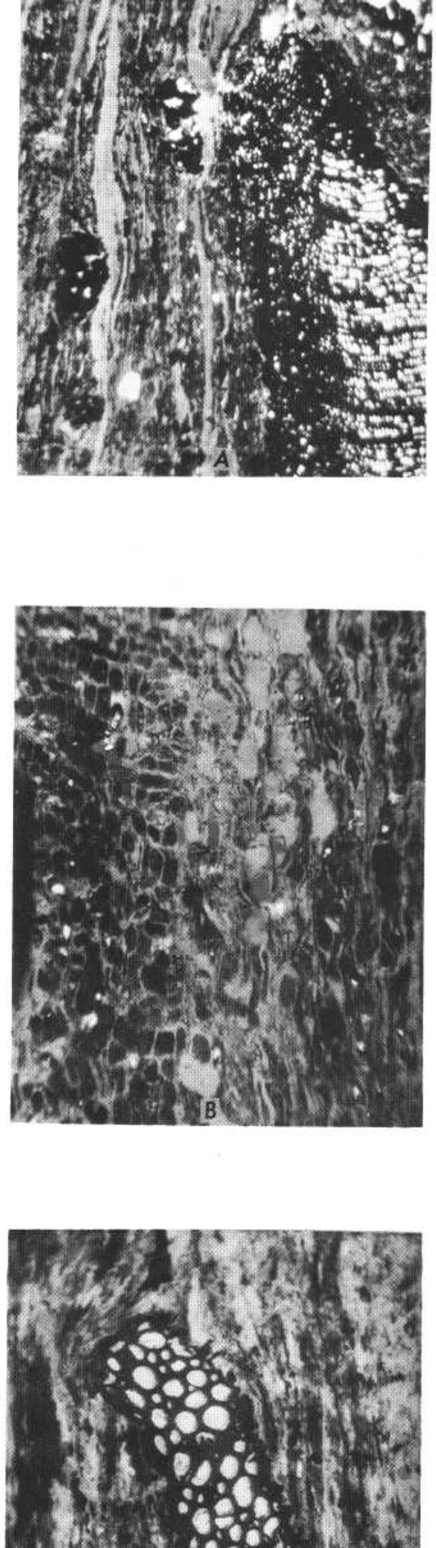
hydrogen. When the oxygen and hydrogen of decaying vegetation are driven off—mostly combined as water—by chemical reactions, heat, and pressure, the carbon remains as coal. The kind, or rank, of coal that results depends mainly on how completely the hydrogen and oxygen are driven off. The quality of the coal depends on how nearly the deposit was pure plant debris to begin with. The coal at Philmont, much like that shown in figure 49, began impure and still contains much moisture (this is why it falls apart so quickly); therefore, it is low in both quality and rank. It is higher rank than peat or brown coal and is classed as low-quality bituminous. Poor as it is, this coal would still be mined at least for local use if Philmont were not near the great Raton coalfield.

Rocks of the hummocky hillsides

The hummocky hillsides are mainly covered with soil, grass, and trees; rare indeed is a glimpse of the rocks beneath. Where visible, the rocks do not have the neat layering of the other sedimentary rocks we have seen but instead are a jumble of sharp-edged blocks of hard rocks, in assorted sizes and shapes, surrounded by fragments of black shale (fig. 51). Most of the blocks are a few inches to a few feet across, but a few are as big as a house. The blocks are not of the same kind of rock everywhere. In the large areas of hummocky landscape west and north of Cimarron town they are mainly yellow and gray sandstone. Those bordering Fowler, Ocaté, and Urraca Mesas are nearly all basalt. Along Ute Creek and near Cimarroncita Girls Camp, they are mainly dacite



COAL AT PHILMONT. A, Abandoned mine (in Vermejo Formation) on west side of Ponil Creek, below gaging station. B and C, Piece of fresh bituminous coal, like that at Philmont, from drill core collected 100 feet below earth's surface. A multitude of worn and decayed plant fragments, solidly packed together. Left view (B) is across the layering; right view (C) is of the top of a layer. Stalks and long narrow leaves are like those of modern cattail. Bottom third of left view is gray shale containing a lens of coal that was once a woody stem. Half natural size. (Fig. 49)



SLICES OF BITUMINOUS COAL magnified 100 times to show some different kinds of plant structures that become coal. (Fig. 50)

ROCK DEBRIS on a hummocky hillside near U.S. Highway 64. The largest blocks are 6 feet across. (Fig. 51)

SLOPE MANTLE, unusually thick, in the mountain country, on the trail near Beaubien Camp. It is only a few feet thick in most places. (Fig. 52) porphyry. In each area, the main hard rocks in the hills above are the same as those in the blocks on the hillside. Black shale underlies the hard rocks near all the hummocky areas.

Without much help from running water, the blocks have simply slid off the nearest hillside, mixing with the shale which acted as a lubricant as they slid. These rock jumbles, then, are landslides. They have not moved much lately, for the trees standing on them are not tilted or toppled and must have grown after sliding stopped.

Rocks of the rugged mountains

Bare rock outcrops are few in the mountain country, except at the mountain front and at the highest altitudes, above timberline. The solid rocks are mostly hidden by a mantle of sharp-edge rock fragments of varied size and shape that have broken off former outcrops and crept, slid, or been washed a little way downhill. These aprons of broken rock in turn are generally covered by soil and vegetation, but their edges can be seen here and there where they have been cut into by streams or by man (fig. 52).

The solid rocks at the jagged mountain front are mostly sheetlike bodies of the same kinds of sedimentary and igneous rocks that underlie the benchlands and plains. But instead of being flat or dipping gently, these sheets stand at high angles; and their upturned edges make ridges if the rock resists erosion, or valleys if it does not. Farther back in the mountain country, however, some bodies of igneous rocks are not sheetlike but are of irregular shape, and some are tremendously large.

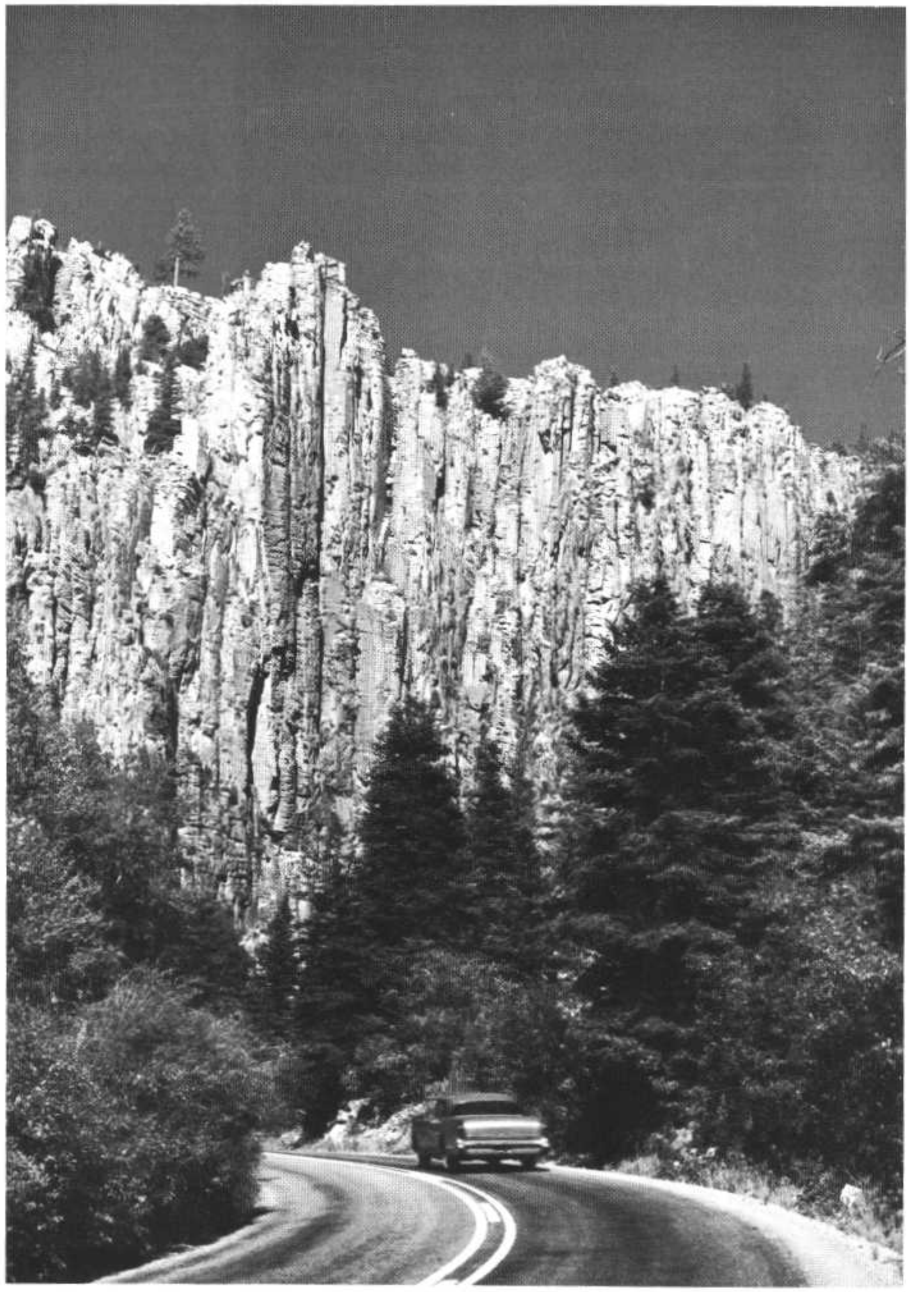
DACITE PORPHYRY—the great cliff maker. A, Lovers Leap, on South Fork Urraca Creek. B, Cathedral Rock, at Cimarroncito Reservoir on Cimarroncito Creek. (Fig. 53)

Spotted dacite porphyry

Dacite porphyry makes nearly all the great ridges and cliffs in the mountain country. The spectacular light-colored cliffs at the mountain front are carved in sheets of this rock: Lovers Leap, on South Fork Urraca Creek (fig. 53*A*); Cathedral Rock, on Cimarroncito Creek (fig. 53*B*); and the Palisades in Cimarron Canyon (fig. 54) are examples. Like the andesite and basalt, the dacite porphyry has innumerable cooling joints, so that it weathers into tall thin columns. The less resistant rocks above and below have been scooped out to make valleys. North of Cimarron Canyon, layers of other rocks thin and disappear, so that Touch-Me-Not Mountain (seen in figs. 75, 76) is mostly dacite porphyry.

The rock is crowded with four different kinds of large phenocrysts set in a fine-grained gray matrix (fig. 55). This rock looks different from the dacite porphyry of the benchlands (compare with fig. 48*B*) only because its phenocrysts are larger and a little more abundant. Most of the phenocrysts are stubby laths of cloudy white plagioclase feldspar. Many are of clear quartz, some having crystal faces but more being egg shaped. Less common are thin bundles of dark-brown biotite plates and rods of dark-green hornblende. Surrounding the phenocrysts are tiny interlocking crystals of orthoclase, plagioclase, quartz, and altered biotite.

This is another igneous rock that crystallized from a melt, or magma, in distinct stages. In the first stage it cooled slowly, so that more than half the melt solidified into large well-shaped crystals. Then cooling was speeded up, and the rest of the melt froze into minute crystals.

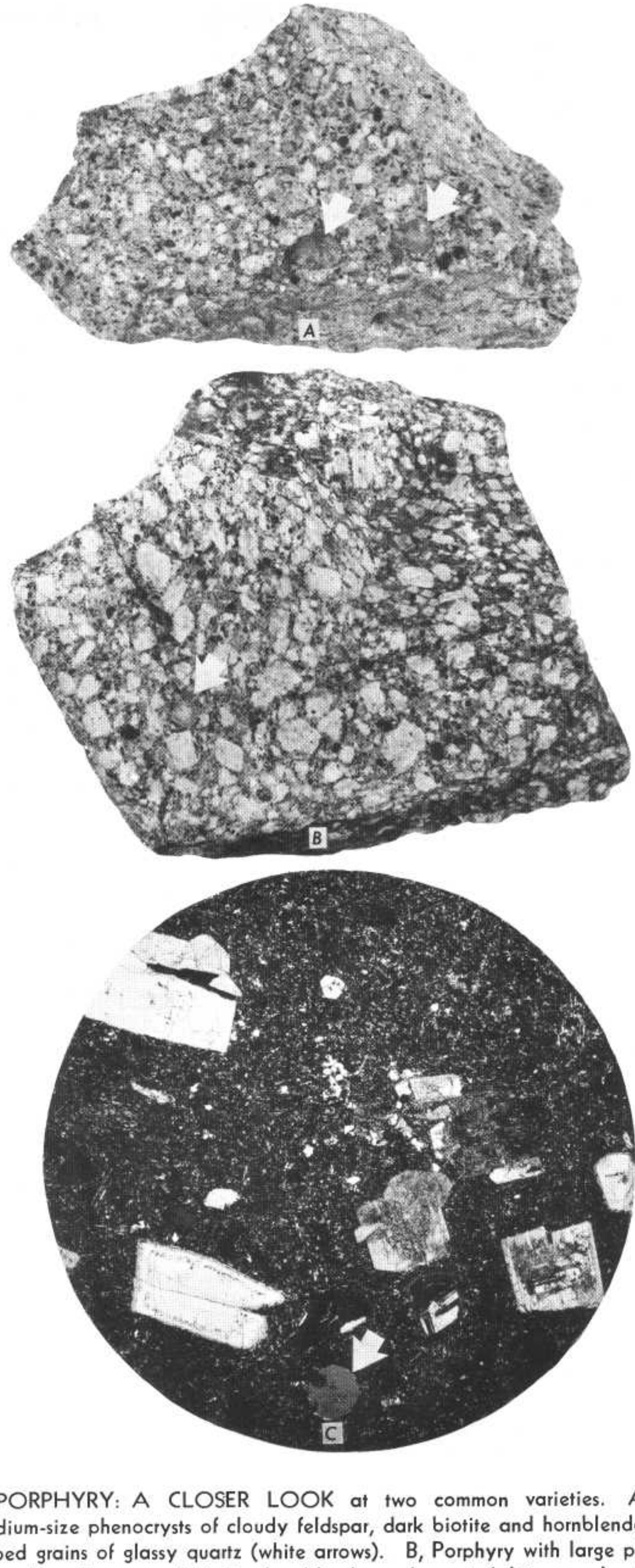


THE PALISADES in Cimarron Canyon. (Fig. 54)

Early in the second stage, the melt attacked and corroded the quartz phenocrysts, rounding them, but freezing prevented the process from going very far. A reasonable guess is that the first stage of slow crystallization was at great depth, perhaps 10 miles or more. The second stage probably followed oozing of the partly solid mush into the cover of colder sedimentary rocks.

Striped gneiss and schist

Gneiss and schist are almost as abundant at Philmont as dacite porphyry, for the heart of the mountains, from upper Cimarron Canyon southeastward to Trail Peak, is made mainly of these rocks. Yet little can be said about them, for, as the timber warns from afar, they are rarely exposed. Scattered small outcrops reveal that these rocks, where unweathered, are fine to coarse grained, hard, and banded or layered (figs. 56, 57). Some bands are several feet thick; others are visible only under a microscope. Hard as they are, these rocks split easily and cleanly parallel to the layering. They are mainly composed of familiar minerals: clear quartz, dull white or pink plagioclase, shiny black biotite, silvery white muscovite, dark-green hornblende, and lighter green chlorite. The grains have sharp crystal outlines and are closely packed. The banding is due to varied proportions of the light- and dark-colored minerals. The grains do not lie at random; their long dimension, if they have one, is parallel to the layering, which, in crystalline rocks like this, is called foliation or schistosity, to distinguish it from the bedding in fragmental rocks like sandstone and shale. It is this alinement, especially of the flaky micas, that makes the rock split easily.



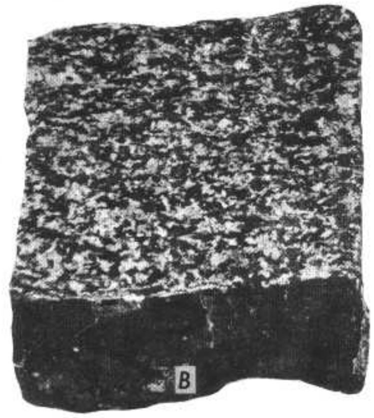
DACITE PORPHYRY: A CLOSER LOOK at two common varieties. A, Porphyry with medium-size phenocrysts of cloudy feldspar, dark biotite and hornblende, and larger egg-shaped grains of glassy quartz (white arrows). B, Porphyry with large phenocrysts of feldspar and smaller ones of biotite, hornblende, and quartz (white arrow). Natural size. C, Slice of dacite porphyry, magnified 8 times. Doubly polarized light. (Fig. 55)

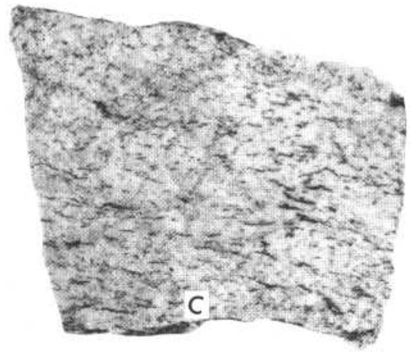
GNEISS—changed from sedimentary or igneous rocks by heating and squeezing deep within the earth's crust. Rare outcrop on Apache Creek. (Fig. 56)

Those striped crystalline rocks that have rather rough and irregular banding and are made mainly of the light-colored blocky minerals, quartz and feldspar, are called gneiss; those that have more even banding and are made mostly of platy biotite, muscovite, and chlorite, or rodlike hornblende are called schist. All gradations between gneiss and schist exist and in some places can be seen in a single outcrop, so we talk about them together. Most of the gneiss and schist is rather coarse grained, but fine-grained gneiss and schist, like that shown in figure 57*E*, can be seen at several places along the east side of the mountain core, such as near the head of South Fork Urraca Creek and in Cimarron Canyon upstream from Clear Creek Store.

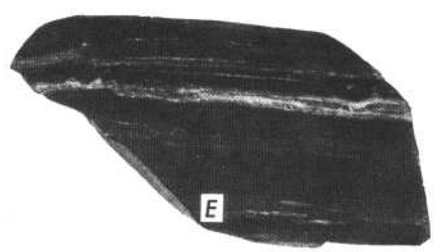
The striped gneiss and schist have some things in common with both sedimentary rocks and igneous rocks, but they are different enough to convince us that they formed in a different way. They resemble waterlaid sandstone and shale in their general mineral content, their rapid changes in composition and grain size, and their layering. Their grains, however, are not rounded but have smooth crystal surfaces with sharp edges and are closely packed. In this they are something like the coarse-grained igneous rocks, but the drawn-out texture and delicate mineral layering of the gneiss and schist are quite unlike anything we have seen in the igneous rocks.

The drawn-out or stretched look in the outcrop exists at a microscopic scale (fig. 58). The rock looks as though it has been squeezed and mashed so powerfully that its grains have been forced into parallel alinement. Some of the platy grains, like the biotite, and the rodlike ones, like the hornblende, seem to have been



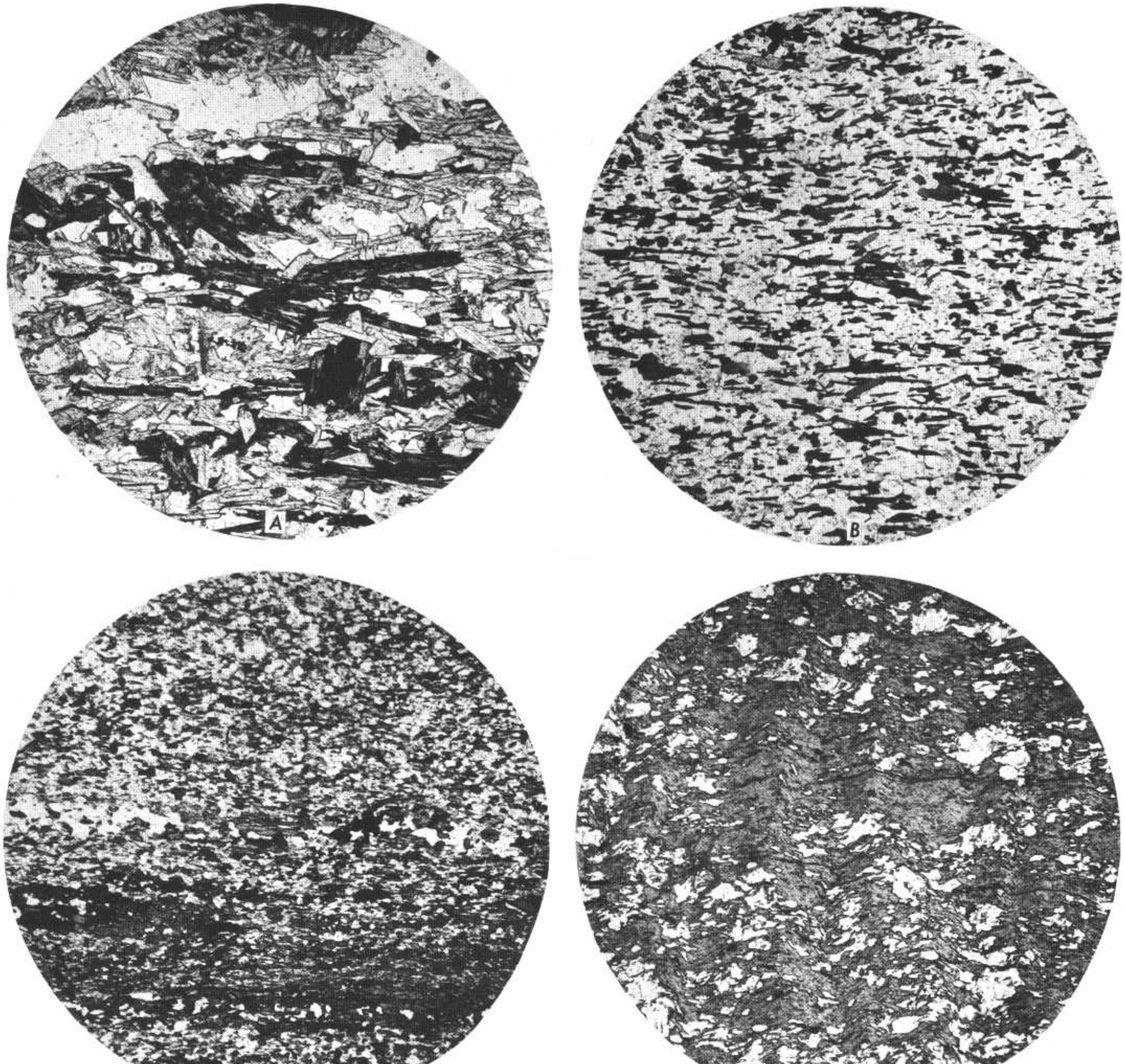


GNEISS AND SCHIST. A, Roadcut in schist at head of South Fork Urraca Creek. B, C, and D, Common varieties of coarse gneiss. Light-colored grains are quartz and feldspar; dark-colored ones are biotite and hornblende. E, Fine-grained schist from head of South Fork Urraca Creek. (Fig. 57)

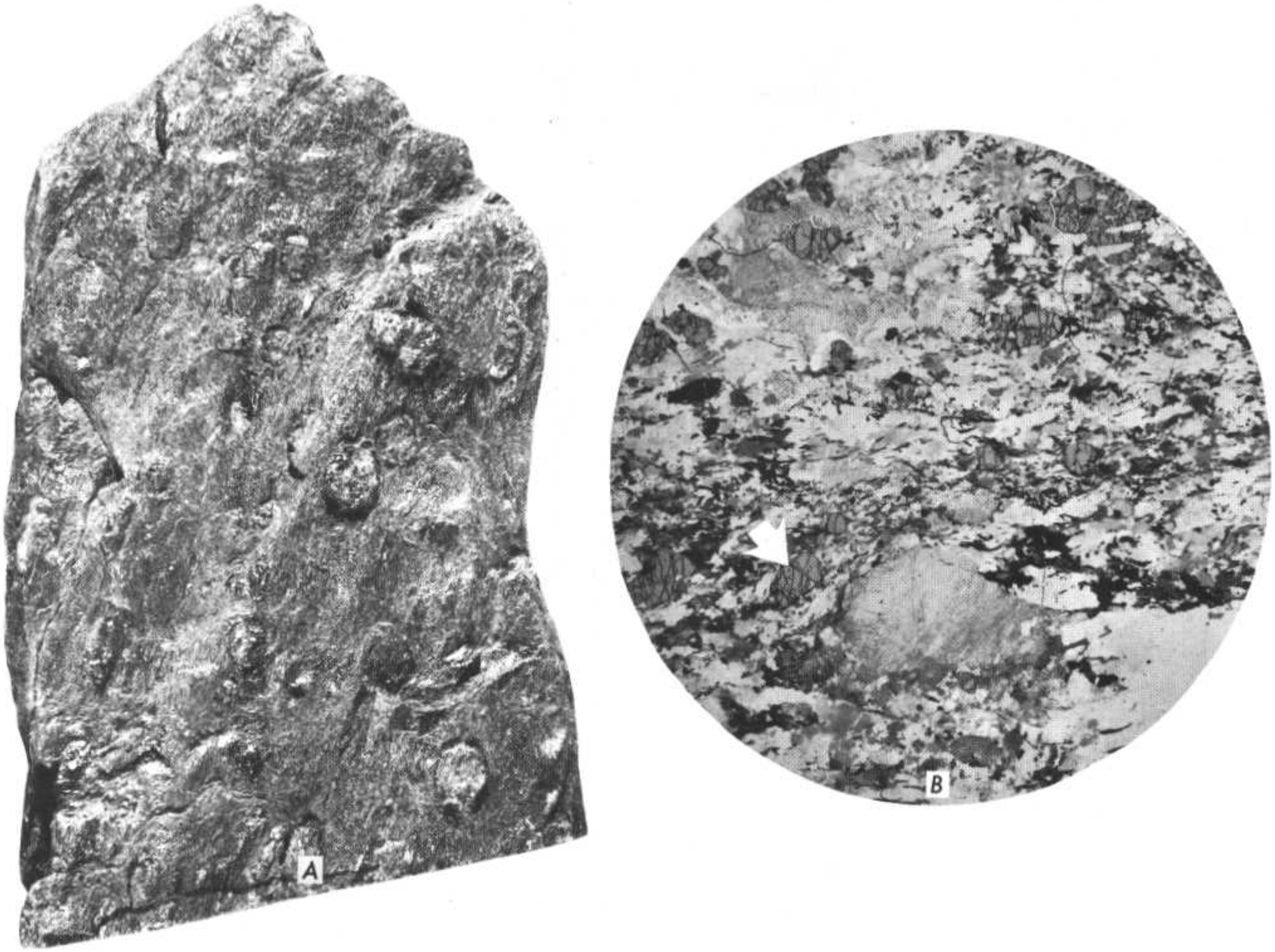


rotated bodily by pressure. Other grains, like the quartz, which is in pods made of many small grains, seem to have responded to pressure by dissolving at points of greater stress and refreezing or recrystallizing at points of lesser stress. The fact that the rotation or recrystallization has produced parallel alinement tells us that the squeezing was not all-sided, as in a swimming pool, but directional, as in a vise. The distinctive shapes and arrangement of the grains also reveal that these rocks grew as they are with little or no melting. If they had been hot enough to melt, except perhaps around the edges of grains, these rocks would have textures like igneous rocks. The original shape, not only of the rock mass as a whole but of each small grain, has changed under directed pressure without much melting. Such rocks that were transformed while solid are called metamorphic rocks, a term derived from the Greek for "change shape" or "transform."

What sort of rocks were transformed to the gneiss and schist of Philmont? In some regions this question can be answered directly by tracing metamorphosed rocks away from areas of compression to places where they are not much changed. This is not possible at Philmont, however, for the gneiss and schist do not grade into less metamorphosed rocks.



GNEISS AND SCHIST under the microscope. A, B, and C, Three common kinds of gneiss. D, Chlorite schist. These views, all magnified 24 times, show the tight packing and parallel alinement of grains that mark most metamorphic rocks. (Fig. 58)



GARNET SCHIST. A, Specimen of garnet schist. The round lumps are garnets, surrounded by chlorite. Natural size. B, Slice of garnet schist, magnified 3 times. Arrow points to one of the many garnet crystals. (Fig. 59)

Work in other regions of metamorphic rocks, such as in New England, the Canadian Shield, and the Scandinavian countries, shows that gneiss and schist like that at Philmont may be transformed either from ordinary sandstone and shale or from common types of igneous rocks. The transformation, however, is not direct, as the rock passes through a long series of changes before reaching the gneiss or schist stage; shale, for example, under mild metamorphism becomes the familiar roofing and blackboard material, slate. The minerals of the new rock may or may not be the same as those of the old rock, as the high pressures and fairly high temperatures of metamorphism may lead not only to rotation and recrystallization of minerals that already exist but also to the growth in place of new minerals better suited to high temperature and pressure, without any additions of matter. For example, part of the clay so common in sedimentary rocks has about the chemical composition of feldspar plus water; the heat of metamorphism may drive off the water of this clay, and new feldspar may form. Chlorite, another component of common sedimentary clay, has a chemical composition similar to that of biotite plus water; it may recrystallize to biotite when the water is driven off. If calcite (calcium carbonate) is present, as it often is, its calcium may combine, during metamorphic heating, with chlorite to form hornblende, and the carbonate may escape as carbonic acid. Of course, if anything besides heat and pressure is added during metamorphism, all sorts of new minerals may form. And, if the rock gets hot enough, it may partly melt and later freeze as an igneous rock.


QUARTZITE from compground west of Clear Creek Store. A, Pieces of quartzite. Natural size. B, Slice of quartzite, magnified 6 times. All grains are quartz. Doubly polarized light (Fig. 60)

Garnet schist

An especially interesting kind of schist exposed at Philmont is garnet schist, which is visible on the trail above the head of South Fork Urraca Creek. Here, scattered in fine-grained hornblende-biotite schist near the outcrop shown in figure 57*A*, are small pink garnets about one-eighth to one-quarter inch across (fig. 59). Garnet is a mineral that is common only in metamorphic rocks. It does not appear in any of the igneous rocks at Philmont, and it is rare in igneous rocks elsewhere. Occasionally, crystals of garnet are found in sandstone, but the edges are always rounded off, showing that the garnet did not grow in the sandstone but was washed in. The garnet crystals at Philmont have grown in the schist as brand-new minerals, as a magnified slice shows (fig. 59*B*). Pink garnets require a lot of calcium, much more than ordinary igneous rocks have; perhaps this schist was once a calcite-rich shale or a shaly limestone.

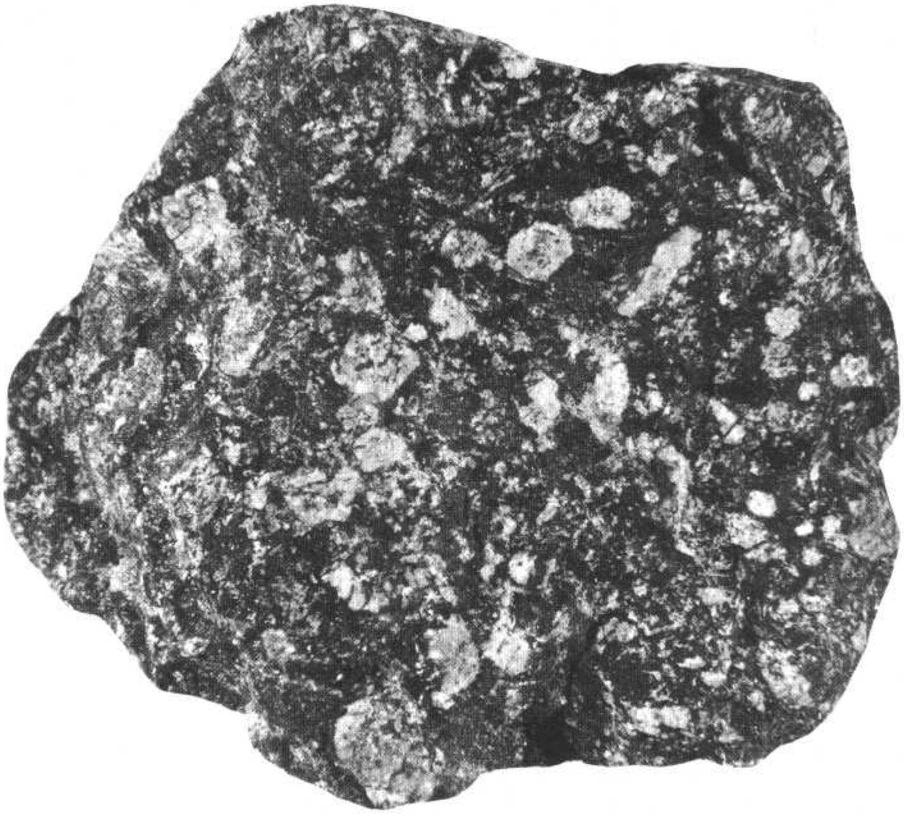
Quartzite

Here and there, especially along the east side of the mountain core, layers of a hard rock made almost wholly of tiny grains of quartz are sandwiched between the layers of gneiss and schist. The grains are tightly cemented by quartz, and the rock is called quartzite. Most of the quartzite layers are only a few inches thick, but some are many feet thick. The thickest and best exposed are in Cimarron Canyon at the west end of the campground half a mile west of Clear Creek Store. The outcrops of quartzite weather to dark colors, but the freshly broken rock is a glassy medium gray and contains scattered hairline streaks of pale green (fig. 60). The green streaks, though hard to see, are parallel to each other and to the layering in the neighboring gneiss and schist. Magnified (fig. 60), the rock turns our to be made almost entirely of tiny irregular grains of quartz. The rock also contains scattered flakes, and bundles of flakes, of white mica and green chlorite that do not appear in figure 60. The grains fit tightly together, as in a mosaic, and the rock has no pore spaces.

This quartzite is just as much a metamorphic rock as is the neighboring gneiss and schist, but a microscope is needed to show that it is, by the shape and arrangement of the quartz grains. If the rock had more platy minerals, it might even be called gneiss. Though it is uncertain whether the common gneiss and schist of the mountains were transformed from sedimentary or from igneous rocks, there is no such hesitation about the parent rock of the quartzite: it was quartz mudstone or sandstone. Sedimentary rocks made almost wholly of small grains of quartz are common, but igneous rocks of such composition and texture are unknown.

Diorite porphyry

Near the head of South Fork Urraca Creek is a single large outcrop of a remarkable rock consisting of giant pale-gray crystals of plagioclase feldspar as much as 2 inches long surrounded by small interlocking grains of hornblende and feldspar (fig. 61). This rock is diorite porphyry. It looks a little like the common dacite porphyry of the mountains, but it is really very different. For one thing, it is a much simpler rock, lacking three minerals abundant in the dacite porphyry—orthoclase, biotite, and quartz.



DIORITE PORPHYRY from South Fork Urraca Creek. Giant crystals of feldspar surrounded by small ones of black hornblende and clear feldspar. Natural size. (Fig. 61)

For another, it has a smeary, fuzzy look. This is because the rock has been partly shattered, dragged apart, and then recrystallized, so that the phenocrysts have jagged rather than smooth edges. This rock seems to have started out as an igeneous rock but to have been changed a little by pressure. In a sense it is a metamorphic rock, but it has not been changed nearly as much as the neighboring gneiss and schist.

Anyone walking up the bed of the South Fork soon becomes aware that this distinctive rock must crop out somewhere upstream, for pebbles and cobbles of it are noticeable for many miles downstream. As similar stones do not appear in any other creek bed, it seems safe to conclude that this outcrop is the only one in the Philmont area.

Outcrops of other rock types can, of course, be predicted in the same way—the diorite porphyry, being both unusual and gaudy, just offers an especially easy spoor to follow. A challenging game is to pick out the different rock varieties in a stream gravel and see how many can be tracked to their outcrops upstream. This is not entirely a game for this is the way many gold and other ore deposits have been found.

Pink granodiorite

Scattered throughout the areas of gneiss and schist, but not elsewhere, are irregular masses of pink granodiorite and similar granitelike rocks. Most of the masses are small and are deeply weathered. A large and well-exposed body of coarse-grained granodiorite, however, is on Highway 64 near Clear Creek Store (fig. 62). The rock is so coarse (fig. 64) that the individual minerals can be identified on sight—they are clear quartz, deep-pink orthoclase, pale-gray plagioclase, and brownish-green biotite.

Similar rocks elsewhere at Philmont are mostly finer grained and contain different proportions of the same minerals; some also contain hornblende. Properly, they should have other names, like granite and quartz monzonite, but we will include them with the granodiorite. In some places the granitelike rock is even coarser than that near Clear Creek Store, in such places it has sheets of mica as much as a foot across and crystals of quartz and feldspar to match. Such aggregates of giant crystals are called pegmatites; those at Philmont have less feldspar than the ordinary granodiorite, more quartz and biotite, and also much silvery muscovite. A piece of pegmatite is shown natural size in figure 63. The crystals are so large that we see all of only one—the dark distorted column of biotite; the rest of the view shows parts of several intergrown crystals of quartz.

The pegmatite is not layered like the gneiss and schist, but it has been somewhat distorted by pressure, as figure 63 dramatically reveals. Normally, biotite crystals form in six-sided columns (fig. 63*B*). The flaking or cleavage that is so characteristic of mica is parallel to the base of these columns. A normal crystal of biotite cut like that in figure 63 would have the shape of a rectangle (fig. 63*C*). The biotite in the photograph has been distorted (fig. 63*D*). The tiny steps on the right-hand edge are places where bundles of cleavage plates have shifted as units in response to deforming stress.

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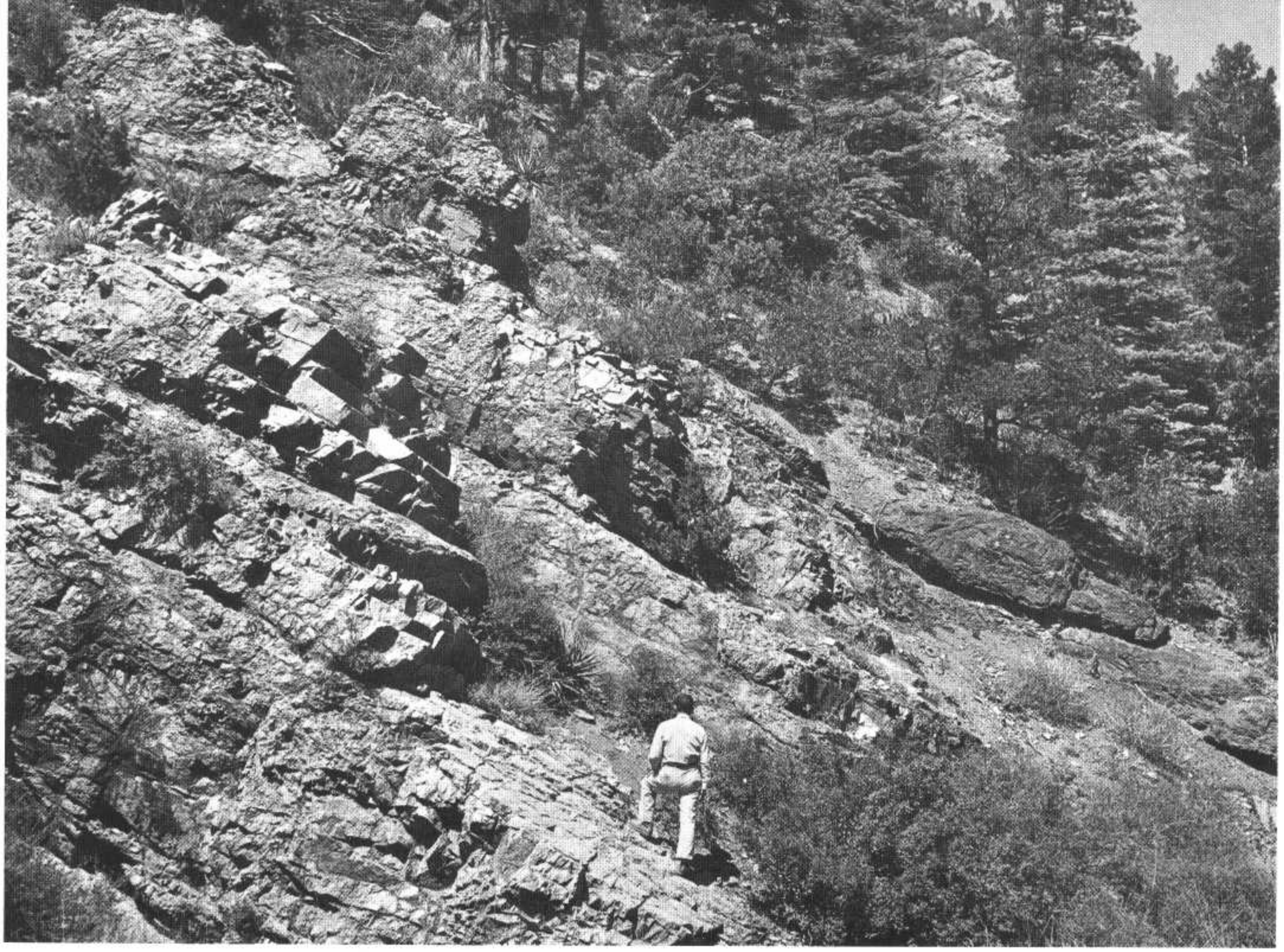
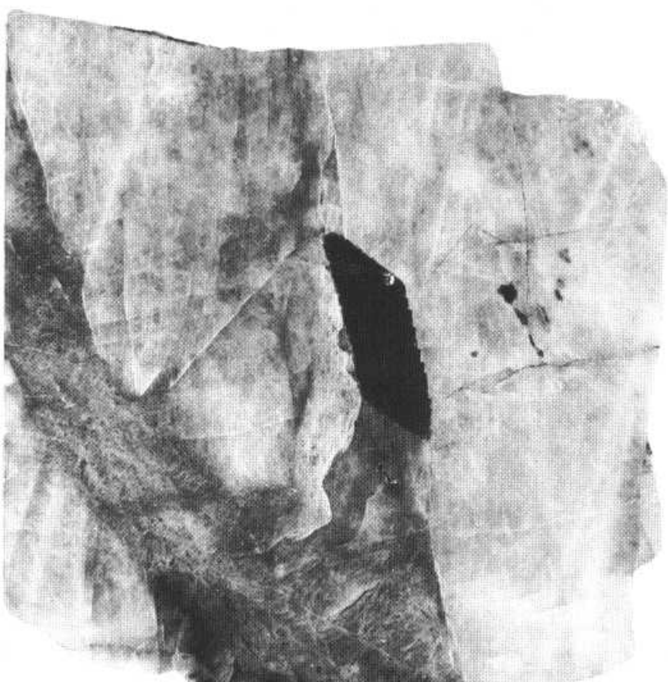


COARSE-GRAINED PINK GRANODIORITE one-fourth mile downstream from Clear Creek Store. (Fig. 62)



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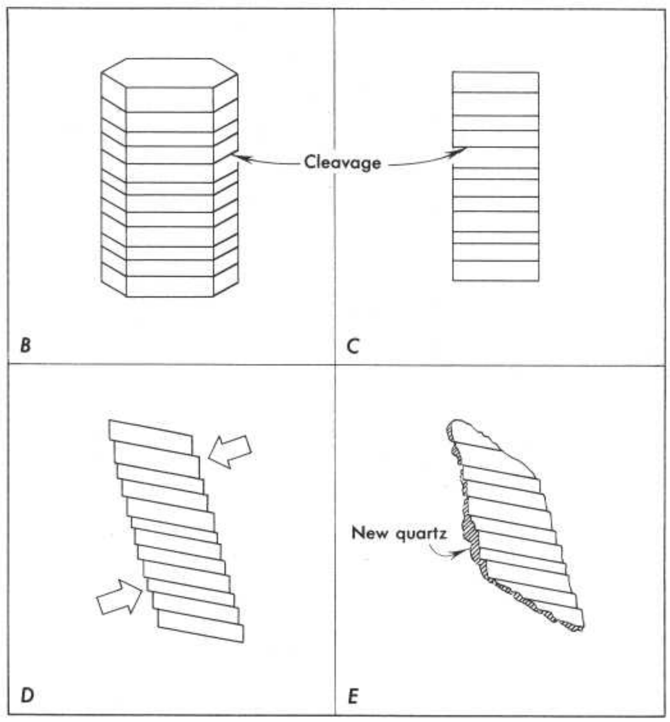
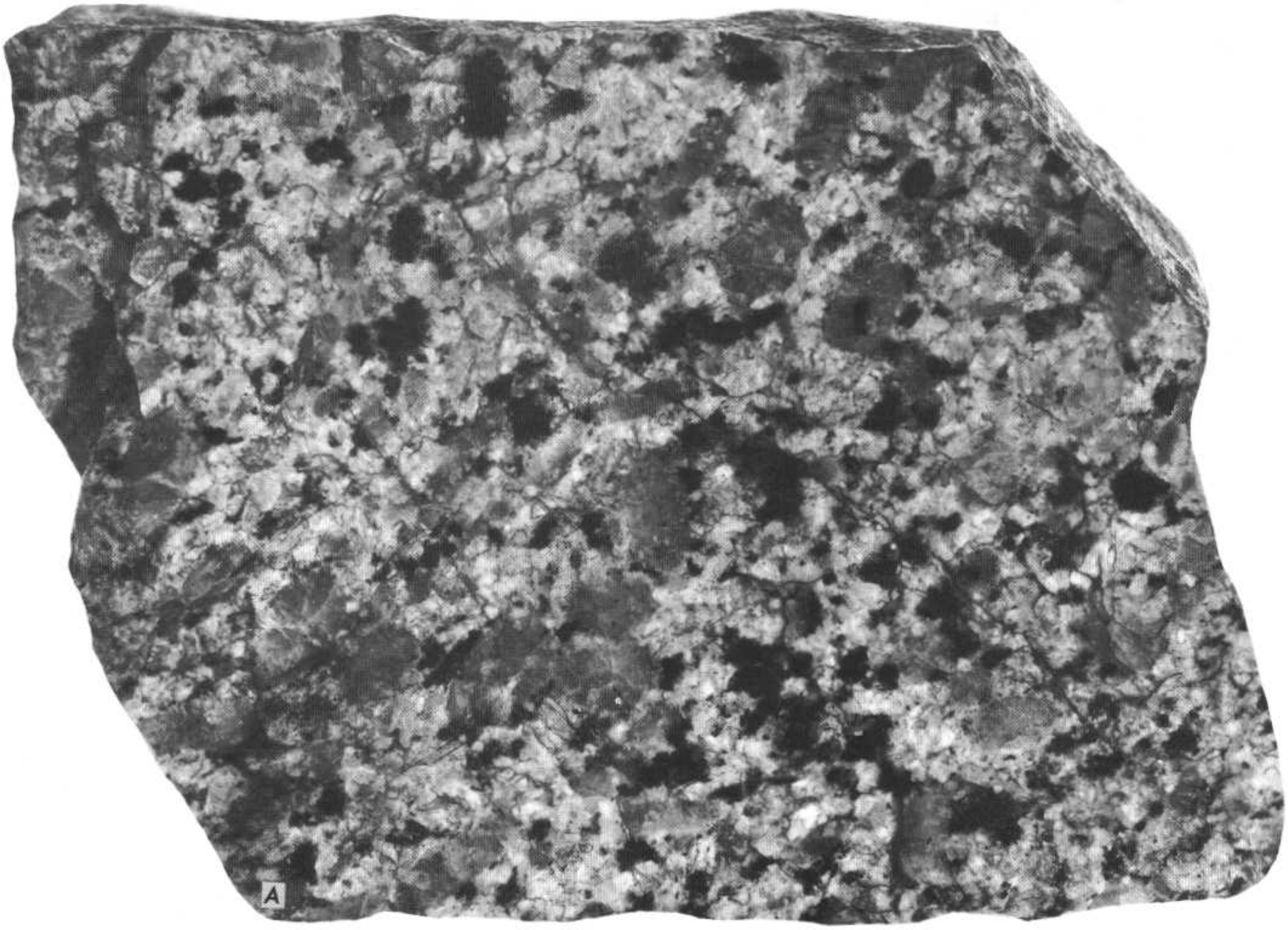
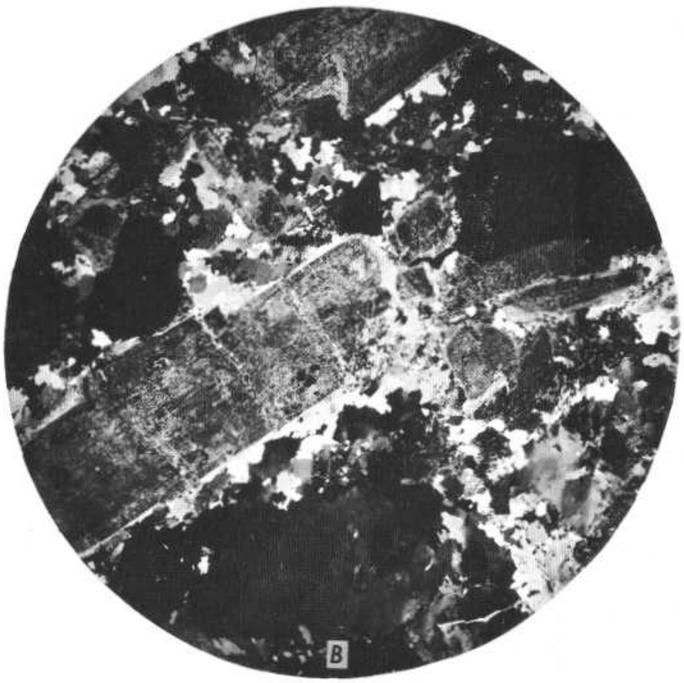


PEGMATITE—a granitelike rock made of giant crystals—from near Clear Creek Store. A, Pegmatite containing distorted biotite crystal. Natural size. This specimen contains quartz and biotite only. The large pod of pegmatite from which it came also displays giant crystals of feldspar and of muscovite. B, C, D, and E, Steps in the distortion of a biotite crystal. (Fig. 63)





CLOSE-UPS OF GRANODIORITE. A, Slab, natural size. B, Slice, magnified 5 times. Doubly polarized light. (Fig. 64)

The steps are absent or are rounded off on the left side (fig. 63*E*). Instead, there is a film of clear quartz between the biotite and the cloudy quartz of the rock. On this side the biotite has been attacked by hot fluids moving along cracks and replaced by new quartz that is darker than the original quartz.

The granodiorite resembles the other igneous rocks we have seen and evidently crystallized from a melt. Its wide range in grain size suggests a wide range in the conditions of crystallization. The first explanation that comes to mind is that the rate of cooling differed from place to place. For example, a small mass of granodiorite magma intruded into solid cold rocks would be expected to cool more quickly and be finer grained than a large mass. If the intruded rocks were almost as hot as the magma, however, even a small amount of magma would cool slowly and end as a coarse-grained rock.

But more than the rate of cooling is involved, for the same small mass may grade in a few inches from fine-grained granodiorite to pegmatite. Understanding begins when we realize that besides being coarser grained than the granodiorite, the pegmatite contains much more water: it is richer in biotite and muscovite, which contain much water, and poorer in feldspar, which contains none. Probably the pegmatite is coarser grained because it crystallized from a part of the magma kept fluid by dissolved water vapor; molecules were able to migrate more easily through it than through the stickier, water-poor parts of the magma, so that larger crystals could grow there during the same time that smaller ones were growing nearby.

Where did the granodiorite magma come from? Granodiorite occurs only in the metamorphic rocks and has the same minerals as the metamorphic rocks, but it differs in texture. A reasonable idea is that the granodiorite represents bands of gneiss that were heated a little more than others, perhaps because they were more deeply buried, and consequently melted enough to flow a short distance and to crystallize with igneous texture. The temperature at which this might happen would vary with the weight of overlying rock and the amount of free water in the gneiss. Laboratory experiments suggest that a granodiorite magma might form at temperatures as low as 1000°F under 10 miles or more of rock cover.

Yellow and gray quartz sandstone

Many prominent light-colored bare ridges in the mountains are made not of dacite porphyry but of sandstone. From a distance it may be hard to tell which is which, but there is no doubt whatever at the outcrop.

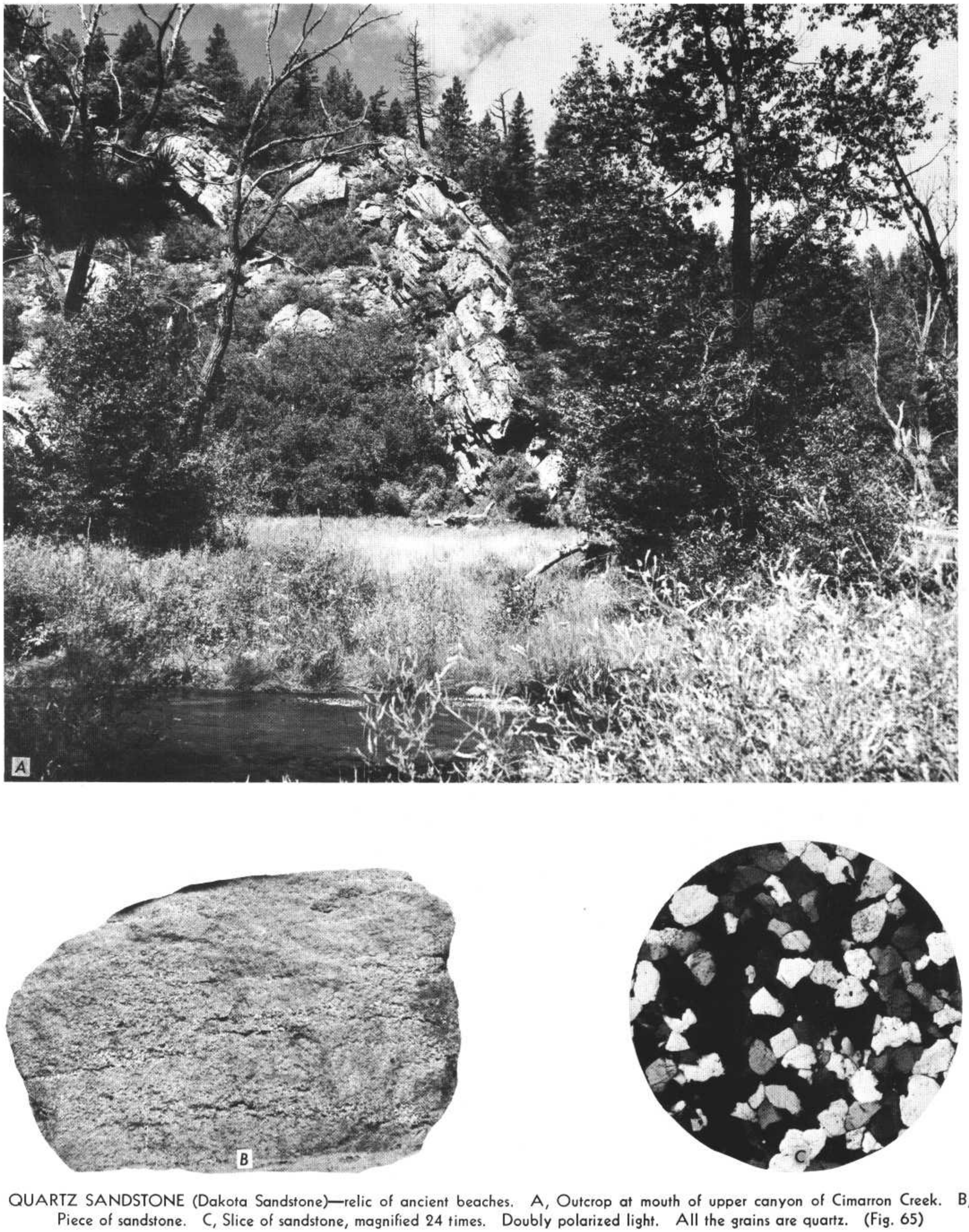
At the eastern mountain front, the first bare ridge that is not dacite porphyry is pale-yellow or gray sandstone, as in the upper canyon of Cimarron Creek where it opens into Ute Valley (fig. 65*A*). Good exposures can also be found farther back in the mountains, especially in the wilderness country at the west boundary of the Scout Ranch, west of Cimarroncito Peak, and north of Comanche Peak. One of the best places to see this rock easily is on the trail along South Fork Urraca Creek (fig. 66). The rock is in beds many feet thick, but weathers into thin plates or slabs. In some places the sandstone is crossbedded like the sandstone of the northern benchlands (see fig. 37).

This sandstone is made almost entirely of quartz; and the grains, many of which have a frosted look, are somewhat rounded, rather uniform in size, and tightly cemented (fig. 65*C*). To distinguish it from sandstone rich in other minerals as well as quartz, we will refer to it as quartz sandstone. The yellow variety is mainly cemented with silica; the gray, with calcite and clay. The rock is broken by irregular fractures which are healed with chalky white calcite or clear quartz. In photographs, the rock looks rather like the quartzite of the mountain country (compare fig. 60), but there is no mistaking the rocks themselves: the sandstone, though hard, breaks around the grains and therefore has lumpy dull surfaces; the quartzite breaks across the grains and has smooth, shiny surfaces.

Most of this sandstone was probably laid down by ocean currents on beaches, as was the gray sandstone of the benchlands, which it somewhat resembles; but the quartz sandstone must have been worked over a great deal more. The crossbedded parts may, however, have been laid down by beach winds rather than by beach waters: they may be fossil dunes. Their crossbedding and texture are like those of existing dunes that are piled up by prevailing winds where there is an abundant supply of sand unprotected by soil and vegetation (fig. 67). Dunes are usually thought of as features of deserts, either far inland, as in Death Valley in California, or along dry hot coasts, as in the Sahara. But there are many dune fields in cool wet climates along open coasts, as on the shores of Lake Michigan or of the Baltic Sea. If most of the quartz sandstone is an ocean-beach deposit, then the crossbedded part no doubt represents coastal dunes. Fossils might help confirm this and also help decide whether the windy beaches were on a hot dry coast or on a cold wet coast, but no fossils have been found in these rocks.

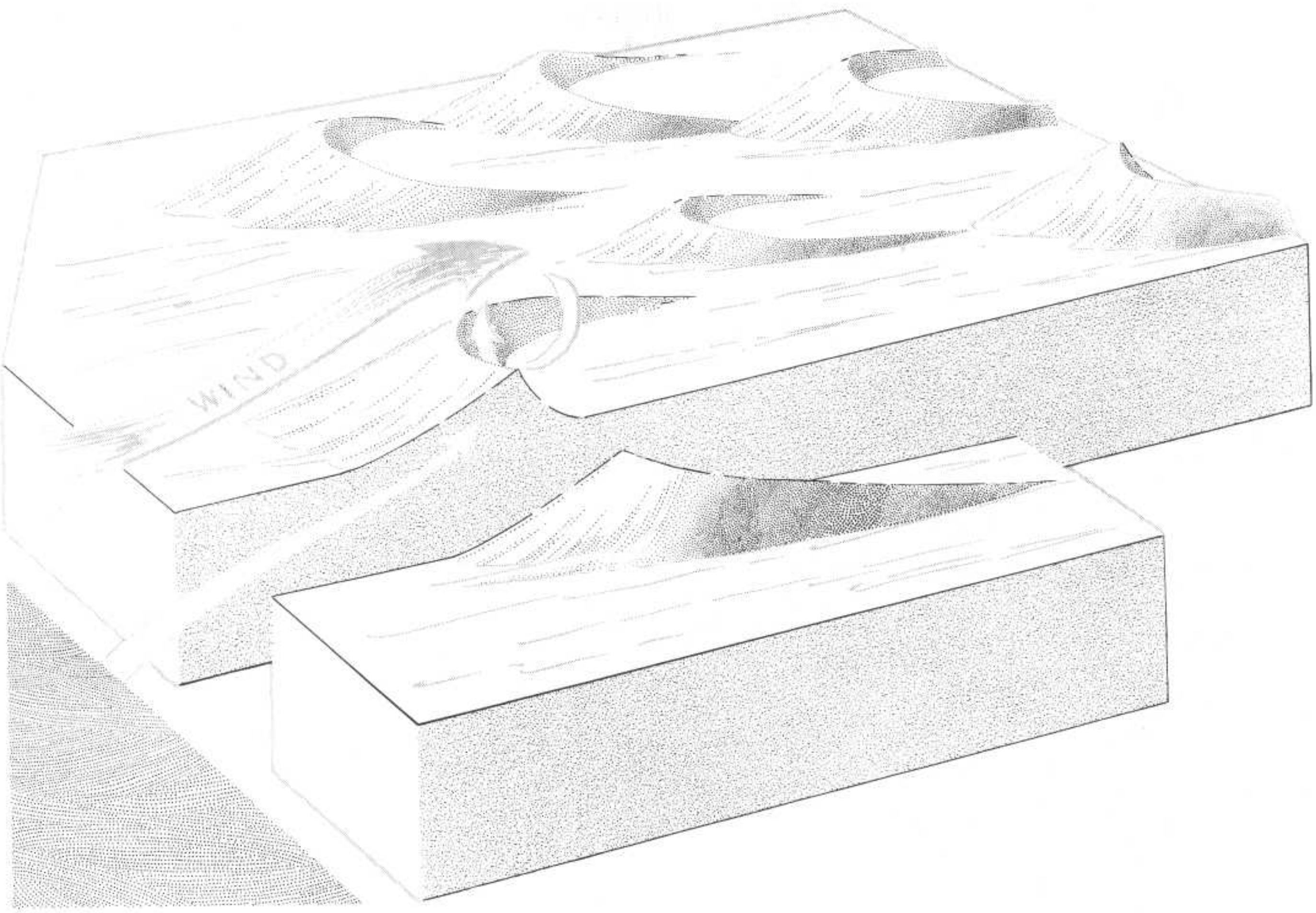
Red sandstone and conglomerate

Low ledges of dark-red or reddish-brown coarse-grained sandstone and conglomerate flank many parts of the mountain core. The only large body of such rocks is on Rayado Creek, where they underlie almost a square mile of canyon land southeast of Rayado Peak. There are good but small exposures along Cimarroncito Creek (figs. 68, 69) and in the northeast slopes of Bear Mountain.



QUARTZ SANDSTONE (Dakota Sandstone)—relic of ancient beaches. A, Outcrop at mouth of upper canyon of Cimarron Creek. B, Piece of sandstone. C, Slice of sandstone, magnified 24 times. Doubly polarized light. All the grains are quartz. (Fig. 65)

QUARTZ SANDSTONE (Entrada Sandstone) on the trail along South Fork Urraca Creek. (Fig. 66)



SAND DUNES: what they are like, inside and out. Neat crescent shapes like these are formed only where sand is plentiful and the wind is from one direction. Most real dunes are much less regular. (Fig. 67)

The sandstone (fig. 70*A*) is made up of large to small poorly rounded grains of quartz, feldspar, hornblende, and biotite, cemented by iron-stained clay and silica.

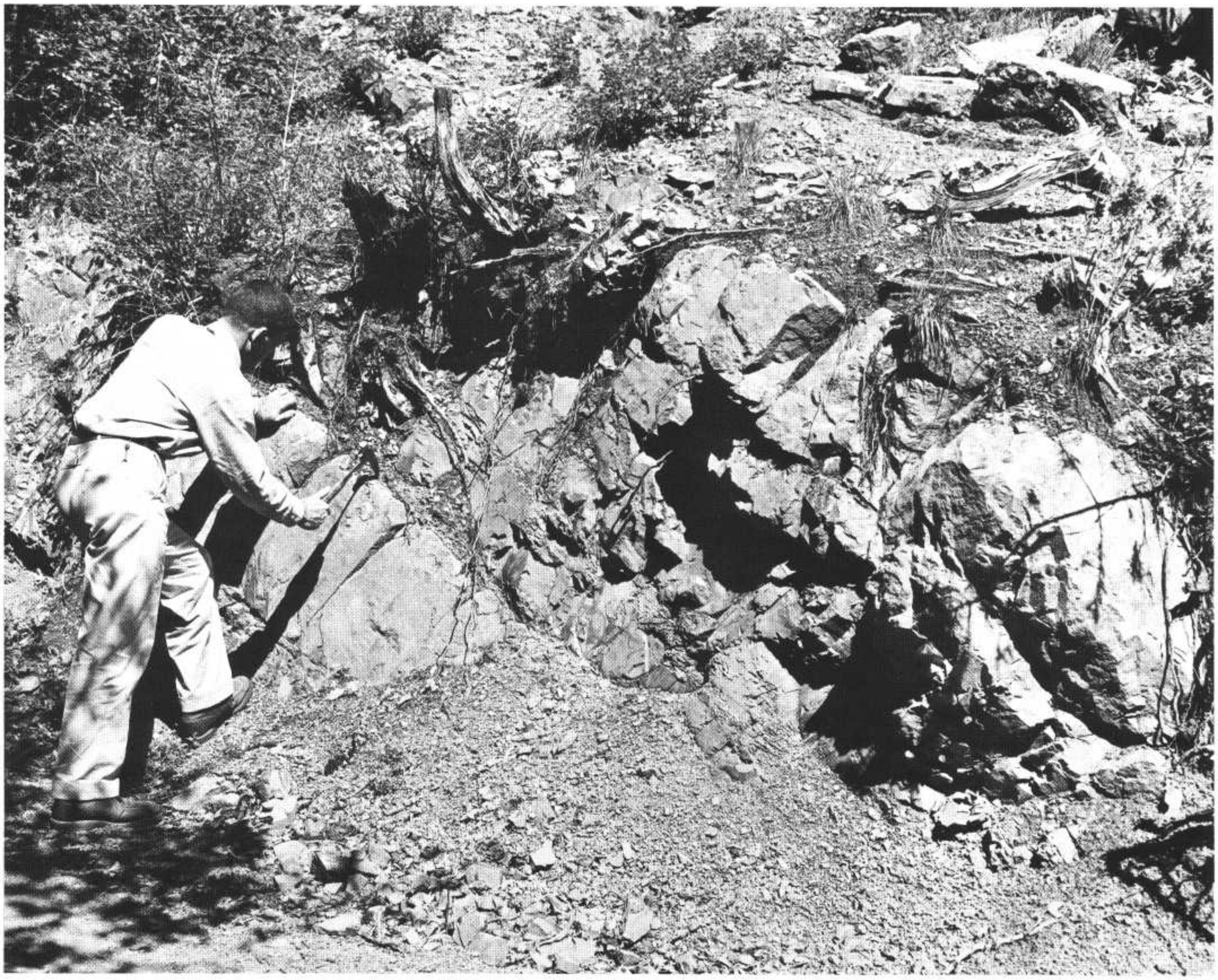
The conglomerate (fig. 70*B*) contains a lot of the same sand, packed between poorly rounded pebbles and cobbles of gneiss, schist, and pink granodiorite.

Along with the red rocks are a few beds of gray sandstone and conglomerate, like the red ones except for color.

These red and gray rocks differ only in color from the yellow sandstone and conglomerate of the benchlands and were no doubt formed the same way—in the channels of overloaded streams. The coarseness, angularity, and poor sorting of the particles indicate that the source areas were not very far away: tens of miles perhaps, but not hundreds. The streams that carried the sediments flowed off an earlier generation of nearby mountains that had a core of rocks like that of the Cimarron Range—gneiss, schist, granodiorite.

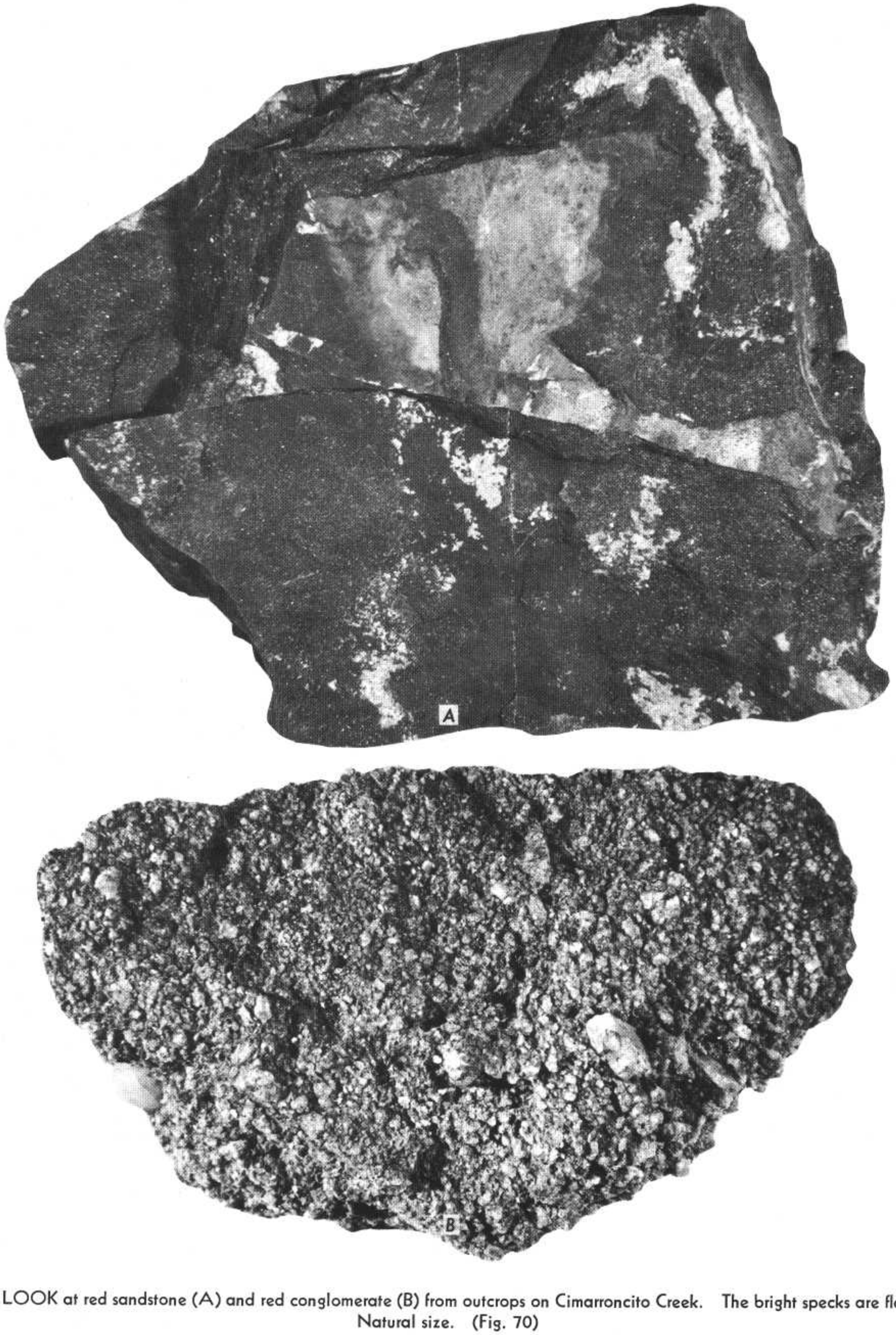
The red color is mainly that of iron hydroxide, often called limonite, which results from the rusting of iron-bearing minerals, mostly magnetite. The iron hydroxide is a thin coating on grains of several minerals, and some is also mixed with the cement. In this way it colors intensely, though it is probably less than 1 percent of the total rock. A little of the redness is from pink feldspar.

Red rocks of this sort are known throughout the Sangre de Cristo Mountains. They crop out on mountain peaks and in deep canyons and have been cut far beneath the surface by mine workings and by drill holes. Probably they are red not because of modern weathering but because they were stained red when deposited. The redness most likely comes from ancient soils that were eroded by the streams and mixed with fragments from other rocks; dark-red soils that could be the source for future red rocks are forming today in many damp



RED SANDSTONE (Sangre de Cristo Formation) deposited by long-vanished streams. Outcrop on Cimarroncito Creek. (Fig. 68)

STREAM-LAID RED CONGLOMERATE (Sangre de Cristo Formation). Outcrop on Cimarroncito Creek. (Fig. 69)



A CLOSER LOOK at red sandstone (A) and red conglomerate (B) from outcrops on Cimarroncito Creek. The bright specks are flakes of mica. Natural size. (Fig. 70) lowlands of the world. The red color suggests, therefore, that the land from which these rocks were worn was deeply weathered and was under conditions of landscape or climate in some way different from those under which the otherwise similar but non-red streammade deposits of the benchlands were laid down. Further clues to these conditions come from fossils in red shale interlayered with these rocks and discussed next.

Red shale and black shale

Red shale and black shale lie beneath much of the mountain front but are easily weathered to soil, so that outcrops are scarce. The black shale is the same as that beneath the plains, and no more need be said about it.

Good but small exposures of red shale can be seen along a few of the main trails, such as near the junction of South and Middle Forks Cimarroncito Creek (fig. 71*A*) and on South Fork Urraca Creek near the foot trail to Fowler Pass. Along with the red shale are a few beds having other colors—mostly brown, green, or gray.

Like the black shale, the red shale is dried, hardened, and compressed mud. The red mud, however, did not settle out on the sea floor but on the flood plains of sluggish streams. The red shale, unlike the black marine shale, has no animal fossils but does have scattered remains of several species of extinct plants (figs. 71*B*, *C*) including the remarkable seedfern (fig. 71*D*). Unlike living ferns, this fern reproduced from seeds, not by spores. The red shale has much more sand-size material—mainly quartz and rock chips—and far less clay and organic fragments than does the black shale. In fact, it is a finegrained version of the streamlaid red sandstones that are interlayered with it.

The plant remains tell a little about the conditions that prevailed when the red rocks were forming. Similar living plant communities do not normally grow at anything like the present altitude or climate of Philmont. Instead, they flourish in damp, warm to cool climates within a few thousand feet of sea level.

Limestone conglomerate

A rare and interesting rock at Philmont is a dark-gray conglomerate made of pebble-size pieces of limestone. This rock, in beds no more than a few feet thick, is only found close to outcrops of red sandstone and red shale (fig. 72). The pebbles are mostly biscuit shaped and have rounded edges, but some are rather sharp edged. They are packed tightly together and are cemented by a mixture of sand and clay.

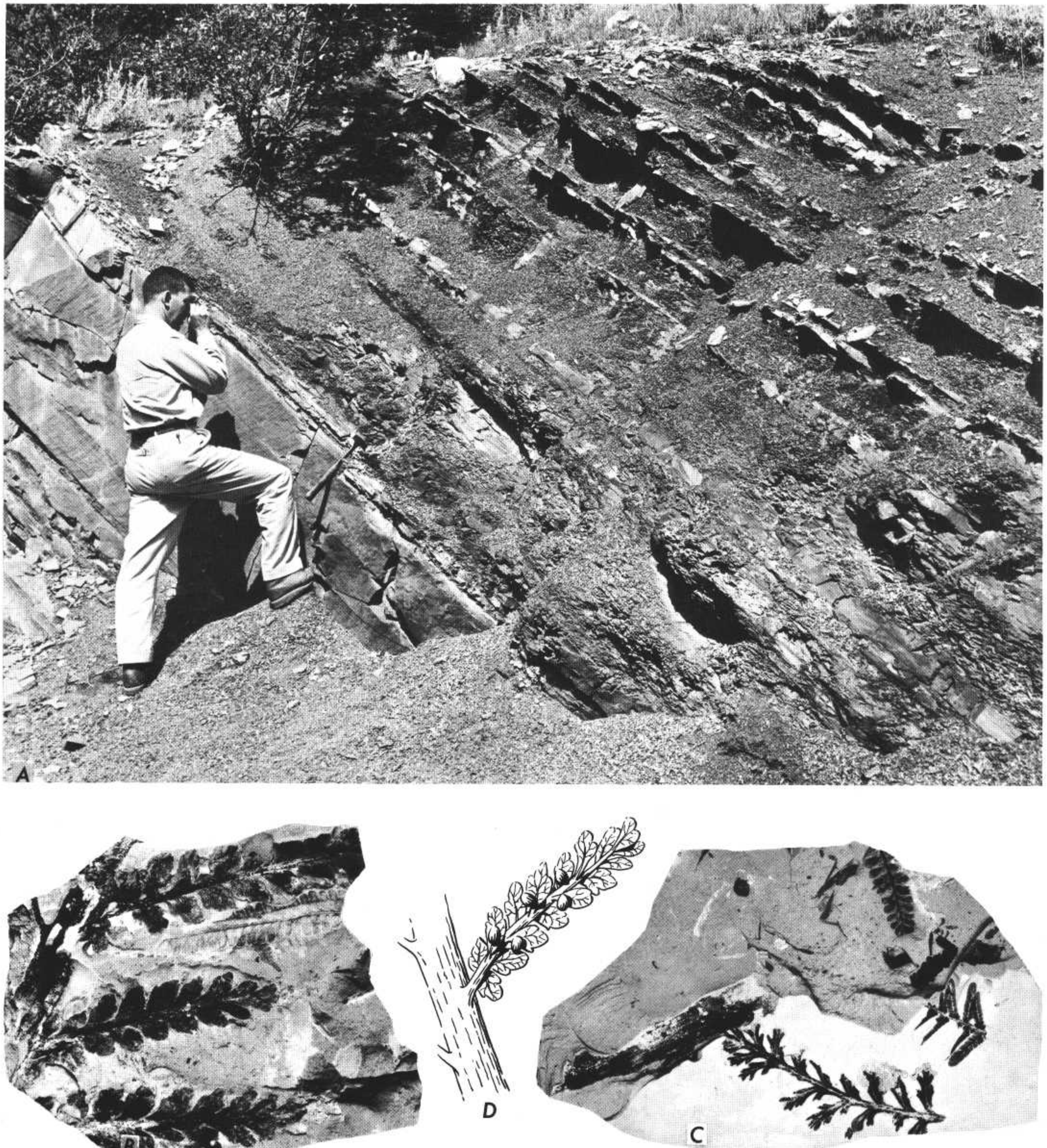
Because the rocks above and below are streamlaid, it seems likely that these thin layers are in some way related to streams. But streams today, even those flowing over limestone that has a pebbly texture to start with, are not depositing layers of limestone pebbles. Because limestone is both soft and fairly soluble, pebblesize fragments do not last very long in streams: they disintegrate very rapidly from chunks to mud. Furthermore, to get a bed of practically pure limestone pebbles means that there must be thick limestone upstream, but there are no suitable sources of limestone nearby; what little limestone is known in the region did not yet exist when the limestone conglomerate was forming.

Very likely, then, the limestone conglomerate is not an ordinary transported sediment. Perhaps the pebbles were formed about where they are in a shallow lake on a broad flood plain. They may have begun on the lake floor as chemical precipitates that dried, cracked into angular bits, and were partly rounded and redeposited by current or storm waves—this sort of almost simultaneous deposition, reworking, and redeposition has been observed in desert lakes. Or the pebbles may be fossils that have biscuit shapes, for certain algae living in modern lakes and in parts of the sea secrete just such masses.

Basalt

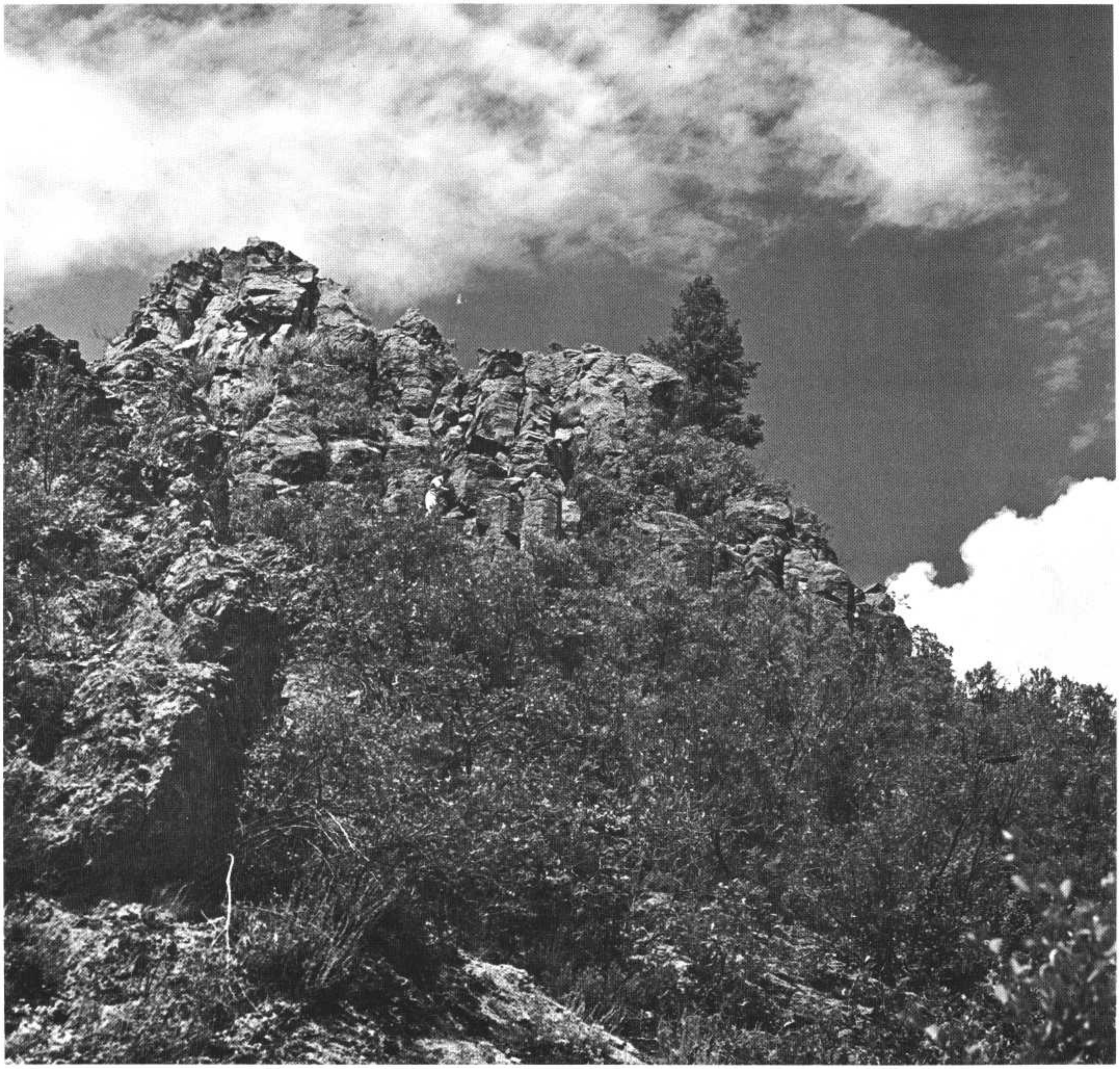
A few small patches of dark basalt cap ridges and peaks at the south edge of the mountain country, near the edge of the basaltcapped Ocaté Mesa. The easiest of these to reach is on the hill above Rayado Base Camp (fig. 73). Another, larger mass makes a little bench at the canyon rim across Rayado Creek from the camp. The largest, but least accessible, of the basalt patches caps Crater Peak and Rayado Peak. Covered by trees and brush, this cap looks very different from the cap on Urraca and Fowler Mesas but is really part of the very same lava flow, cut through by streams.

Most of the basalt is in every way like that on the Ocaté Mesa. On the south side of Crater Peak, however, are a few thin layers of bright-red basalt and of nearly white basalt that look very much like the quartz-rich lava called rhyolite. Probably these brightly colored layers were originally no different from ordinary dark-gray or green basalt but were attacked by the hot gases, mainly steam, that usually accompany volcanic activity. The gases oxidized the green ferrous iron in the basalt to red ferric iron, to make the red variety, and went even farther to make the white variety by dissolving and removing much of the iron and altering the original glass and feldspar to earthy clay minerals.



RED SHALE (Dockum Group) laid down on the flood plain of an extinct river. A, Outcrop near the junction of South and Middle Forks Cimarroncito Creek. The thin beds are shale; the thick beds are red sandstone. B and C, Imprints of extinct plants in red shale. D, Drawing of fronds and seed pods of an extinct seed-fern from red shale. Living ferns do not have seeds, but reproduce by spores. (Fig. 71)

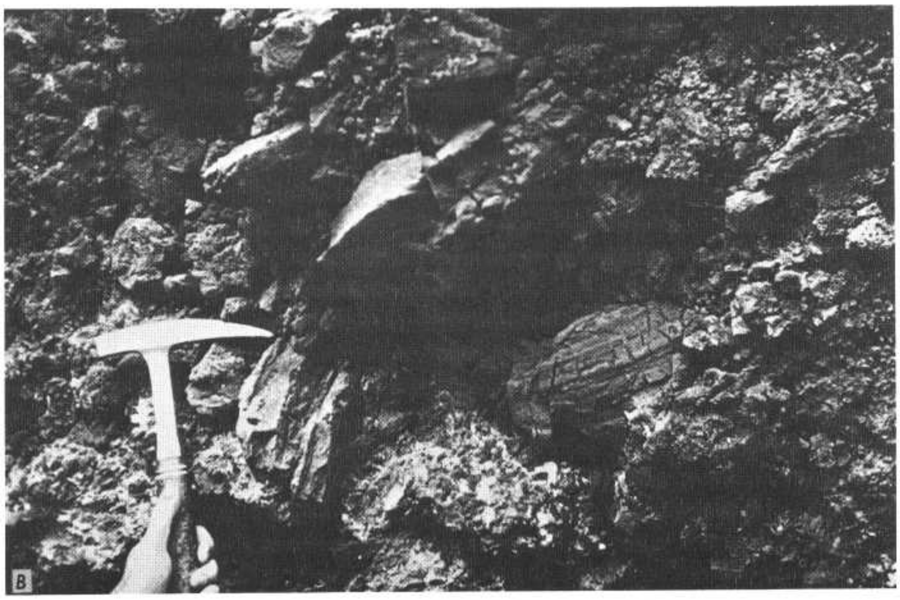
LIMESTONE-PEBBLE CONGLOMERATE, South Fork Urraca Creek. Interlayered with stream-laid rocks, it was probably deposited on land (Fig. 72)



REMNANT OF BASALT LAVA FLOW on hill above Rayado Base Camp. (Fig. 73)

Red bomb beds

Between some of the layers of brightly colored altered basalt lava on the south side of Crater Peak are a few thick stubby beds of red scaly volcanic bombs. Figure 74 shows both a bomb layer and a close-up view of some typical bombs. These bombs were not made by simple outflow of liquid lava. Rather, they are cooled masses of lava that, while still hot enough to flow, were hurled high in the air during especially violent eruptions. During flight they rotated and spun out into bomblike shapes. Meeting cold air, their skins chilled quickly to a breadlike crust, preserving the projectile forms. Large bombs like these are not thrown very far from a vent; so we can be sure that Crater Peak is well named, even though it does not have the cone shape we might expect of a volcanic mountain. During flight the bombs may have begun to oxidize, making them red; but they probably were not in the air long enough for the process to go very far, and it was very likely completed on the ground by hot gases rising through and around them from below. The bombs are so much altered that it is hard to say what kind of rock they were to begin with. The only minerals we have identified in them are shapeless bits of iron hydroxides and clays and rounded blobs of quartz.

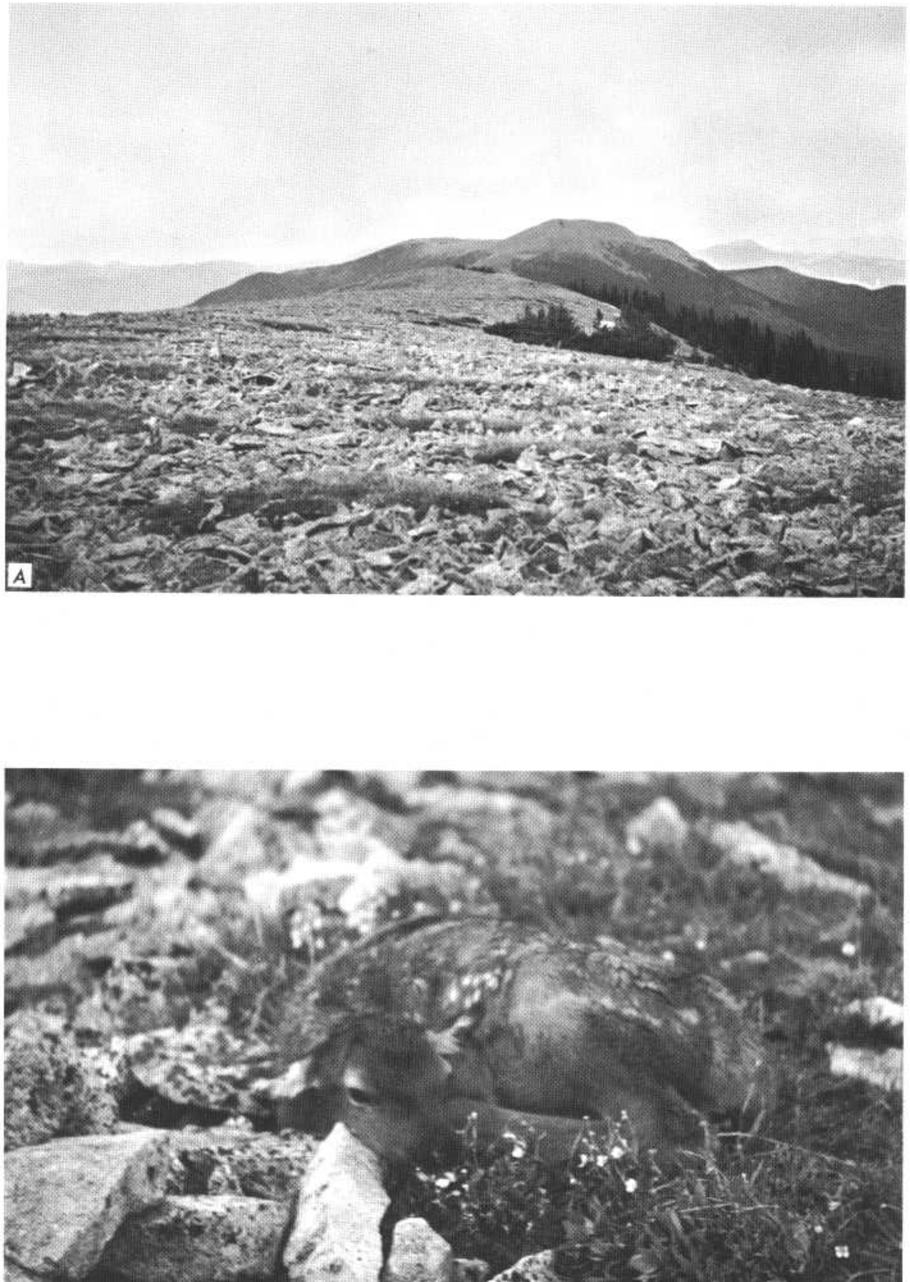


RED VOLCANIC BOMBS from the flank of Crater Peak. A, Bomb layer. B, Close-up of typical bombs. Hurled in the air as red-hot blobs of still-liquid basalt lava, they spun into bomb shapes and froze in the air, some with crusts like that of bread. (Fig. 74)

Pepper-and-salt diorite

Many small masses of dark diorite crop out in the mountains. Most of them are sandwiched between the layers of gneiss and schist, but a few are in the sedimentary rocks. The largest and best exposures are on Cimarron Creek, just upstream from the Palisades. If the light-colored dacite is described as "salt-and-pepper," the dark-toned diorite is "pepper-and-salt." The "pepper" is dark-green hornblende and a little biotite; the "salt," plagioclase feldspar and a little quartz. Not all the diorite is evenly coarse grained like that illustrated. Some is so fine grained that the crystals cannot be seen without magnification. In larger masses the cores are coarse grained and the borders are fine grained; in places the rock is porphyritic, containing scattered plagioclase phenocrysts.

The diorite was probably intruded into the surrounding rocks when they were comparatively cold. The borders of the intrusive body, chilled by contact with the cold rocks, solidified quickly and became fine grained. In the more slowly cooled core, larger grains grew.



BLOCK FIELD, formed on gently sloping land. A, Continuous block field. B, Close-up view of stone net; elk calf in center. (Fig. 75)

Rubble

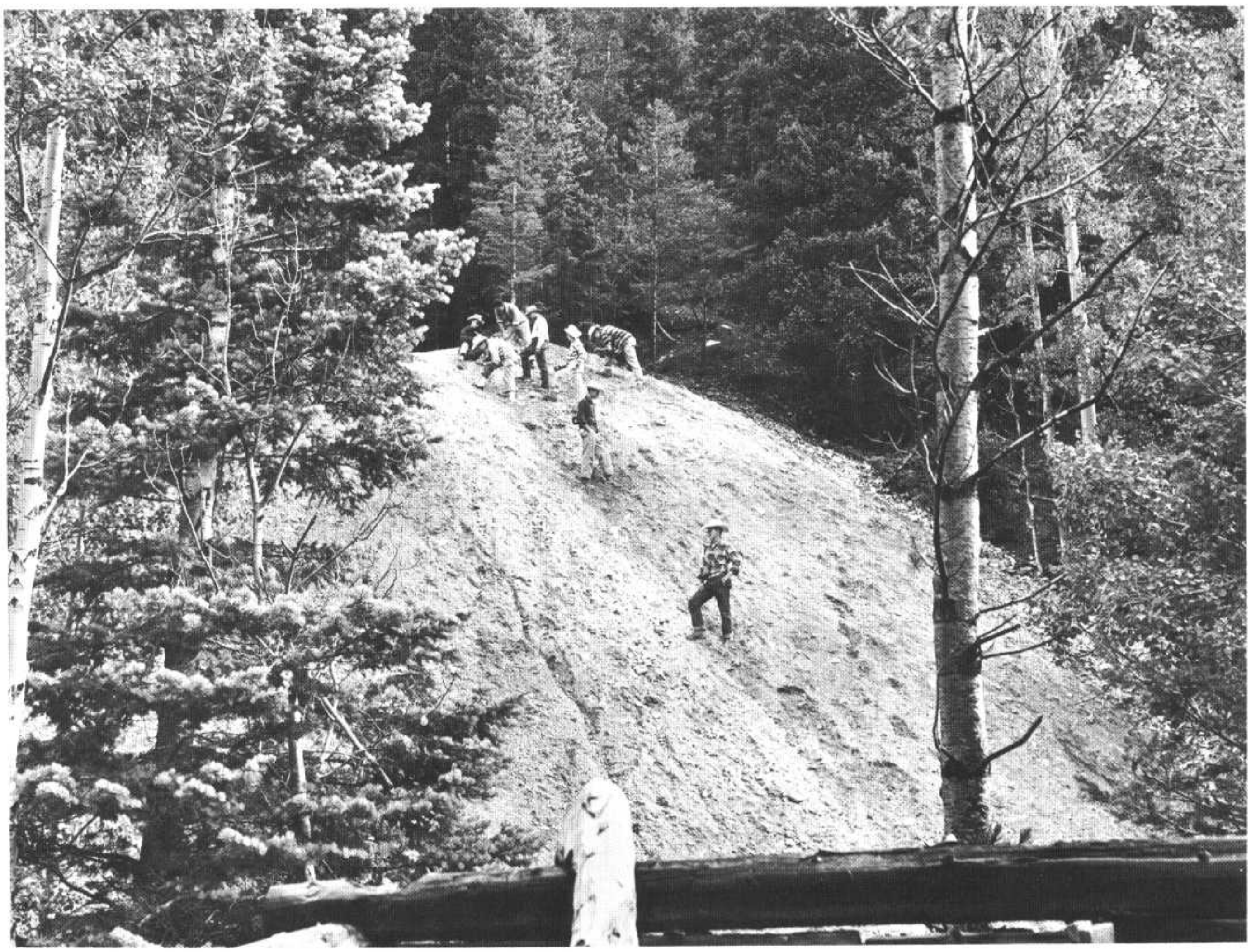
We will speak briefly about one kind of rock that can be seen only after some effort. Far from roads or trails, near timberline on Touch-Me-Not and Baldy Mountains, the bare rock surfaces are mantled with sharp-edged rubble. By watching long enough, we learn that this rubble is the result of frost action. First, rain and melt water work down into cracks in the rock; when this water freezes, it expands, widening the cracks and eventually causing pieces of the rock to break off. On very low slopes, the rubble does not move far but forms large fields of sharp-edged blocks (fig. 75*A*) or forms stony networks around clumps of grass or stunted trees (fig. 75*B*). On steeper slopes, masses of blocks lubricated by rain or melt water sometimes flow slowly downhill like a glacier and come to rest in long, low ribbonlike piles (fig. 76). The furrowed treeless slope in the center of the view in figure 76, on the east flank of Touch-Me-Not Mountain, is made by a large rubble stream. The furrows show that the stream moved in waves.

Ore deposits?

Knowing that gold has been mined high on Baldy Mountain in and near dacite porphyry sheets, we are not surprised to find mine workings near outcrops of dacite porphyry on the northeast slopes of Comanche Peak. Near the heads of both Middle Fork and North Fork Cimarroncito Creek are several short tunnels that have bare piles of broken rock at their mouths (fig. 77). These workings, like those near Baldy Mountain, are abandoned. Indeed, no ore worth mining seems ever to have been found in the few years of prospecting, early in the century, when these tunnels were dug.

BLOCK STREAM, formed on steeply sloping land. (Fig. 76)

EXPLORER SCOUTS ON THUNDER MINE DUMP, Middle Fork Cimarroncito Creek. (Fig. 77)



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In the dirt-encrusted tunnel walls and in fragments of altered limestone, sandstone, shale, and dacite on the dumps are only a few signs of ore minerals: scattered crystals of yellow pyrite, red-gold chalcopyrite, and silvery specularite, and films of green malachite. No gold is visible (it is rarely visible even in rich deposits); but some fairly high gold contents were reported in old assays, and gold colors can be panned in places downstream on Cimarroncito Creek. Rusted mining tools and machinery left behind by the disappointed miners are perhaps more interesting than the specks of ore minerals.

It is not hard to decide where the malachite films came from: ground water containing carbon dioxide has dissolved chalcopyrite (copper-iron sulfide) and precipitated malachite (copper carbonate + water). But how the chalcopyrite itself and the other ore minerals got into the rocks we cannot tell from the tantalizing bits of evidence, except that they seem in some way related to the dacite porphyry sheets. Most gold-copper deposits the world over are in fractures in and near granitelike igneous rocks, suggesting that the metallic minerals were deposited by hot fluids that rose from below soon after the igneous rocks solidified.

Thoughts about rocks

Thinking about the rocks of Philmont, we become aware that, in spite of their great diversity—in appearance, color, hardness, grain size, resistance to erosion, and so on—they formed in only three ways. They are either sedimentary rocks that settled out of some transporting medium, generally water; or igneous rocks that cooled from a melt; or metamorphic rocks that were changed in the solid state from preexisting rocks by great heat and pressure. In this the Philmont region, a mere speck on the planet, provides a fairly good sample of the earth's skin, which is made wholly of rocks that are either sedimentary, igneous, or metamorphic.

Of the sedimentary rocks at Philmont, most were transported and deposited on land by streams, but some formed in the sea. (Most sedimentary rocks of the world, however, were laid down in the sea.) Wind may have made some of the crossbedded sandstones of Philmont. Gravity, of course, governed the moving and dropping of all the sediments and was, with little help, responsible for the hummocky landslides and the mountain rubble deposits. But we found no rocks of the sort that are made by glaciers, and we conclude that there have been no long-lived glaciers in the Cimarron Range, high as it is or may have been.

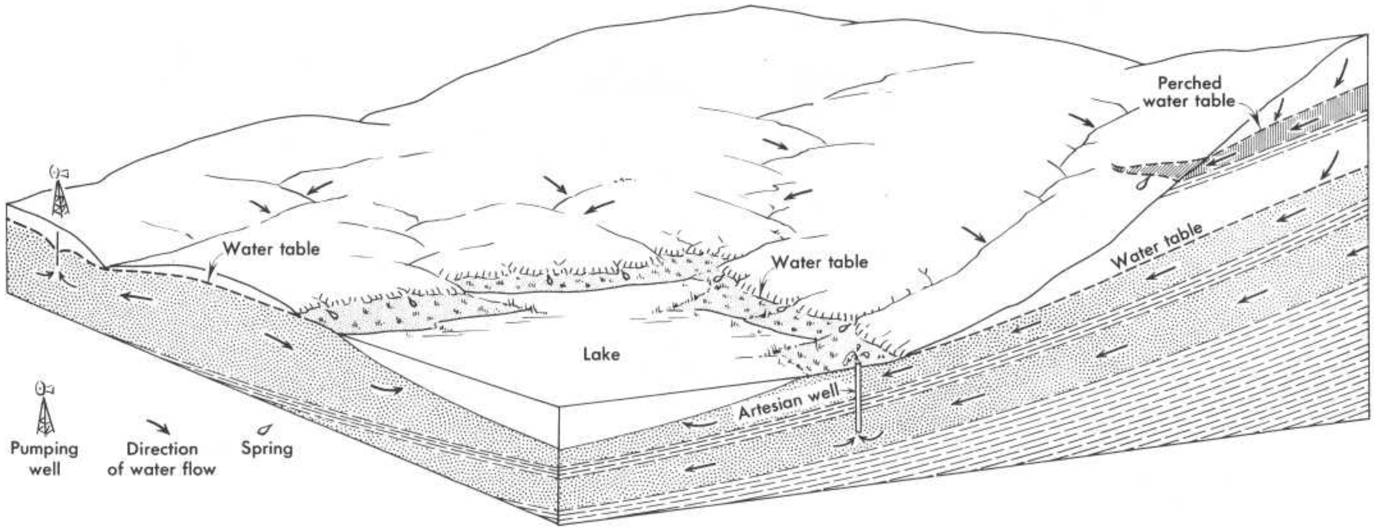
We have met many varieties of igneous rocks, from wholly coarse-grained ones that cooled slowly at depth, through porphyries that had distinct stages of cooling underground, to glassy frothy lava chilled by the cold air at the surface. Several kinds of common igneous rocks that we might have hoped to find are missing, however: there is no granite; there are no fine-grained glassy lavas of the same composition as the dacite, granodiorite, diorite, lamprophyre, or andesite, all of which cooled below the surface; and there are no coarse-grained rocks chemically like the basalt lava. Too, there are only the small area of bomb beds at Crater Peak and the scattered thin layers of orange shale to remind us of the igneous rocks, abundant in many parts of the world, that settle out of the air after explosive volcanic eruptions.

Our assortment of metamorphic rocks is skimpy, and our knowledge of those which do occur is slight. For example, Philmont has no marble, the familiar rock that is metamorphosed limestone. Also missing are the many kinds of metamorphic rocks in which minerals that are rare in sedimentary and igneous rocks have grown in profusion, like the garnet in garnet schist.

Too, we have seen almost nothing of those odd and rare but potentially valuable rocks called ore deposits, and we have given little thought to how they form.

Varied as they are in origin and appearance, the main rocks of Philmont—and of the earth—are made mostly of only a dozen or so minerals. We have named about 30 minerals and probably could find small amounts of several hundred if we looked hard enough, but only a few are abundant enough to be thought of as rock formers. The most common minerals at Philmont are quartz, plagioclase, hornblende, and biotite, and they are very common in all three classes of rocks. Other rock-forming minerals are orthoclase, pyroxene, olivine, muscovite, chlorite, calcite, clay, and coal. Of these, muscovite is widespread in all three rock classes. Pyroxene and olivine are abundant only in the dark-colored igneous rocks; orthoclase, in the light-colored igneous rocks; and chlorite, calcite, clay, and coal, in the sedimentary rocks.

The differences among the three classes become even smaller when we realize that some of the minerals that are more or less limited to one class are really very much like minerals common in the other



WATER IN THE GROUND: the lake beneath us. (Fig. 78)

classes. For example, chlorite is chemically much like biotite and hornblende but contains more water than either, and clay is chemically like feldspar but contains water. We realize, too, that although the metamorphic rocks have a few unusual minerals, like garnet, they are mainly made up of the minerals common to the igneous and sedimentary rocks.

We have actually seen sand and gravel forming at the surface from the weathering and erosion of sedimentary, igneous, and metamorphic rocks. This process also goes the other way, as sediments are deeply buried, compressed by their own weight, and heated. First, they become dried out and cemented; then, as temperature and pressure increase, they are transformed to metamorphic rocks; and then, in turn, if they get hot enough to melt partly or wholly, they may begin to flow and, later, to cool as igneous rocks. The principal chemical change in weathering is a gain of water, both in the rock pores and in the minerals themselves. The principal chemical change in metamorphism is the loss of water. So we come to think of the rocks of the continents as endlessly but slowly passing through a cycle of crystallization⟶weathering⟶erosion ⟶sedimentation⟶recrystallization; they gain water near the surface and lose it at depth. Perhaps some of the rocks of Philmont have been through more than one complete cycle, whereas others—such as the basalt lava—may be on the earth's surface for the first time.

Water in the ground: The lake beneath us

Most of Philmont's surface materials have plenty of open spaces. Soil, gravel, sand, sandstone, and conglomerate all have many obvious air spaces, or pores, between grains—usually 10 to 30 percent of the total rock volume. Even the igneous and metamorphic rocks, whose crystals are tightly interlocked, have many open cracks near the surface. When rain falls or snow melts, part of the water trickles down through these openings. Not many thousands of feet below the earth's surface, however, all the openings in rocks, both pores and cracks, are closed by rock pressure, cementation, or crystallization, as is shown by deep borings and by laboratory experiments. Eventually, the water reaches a level below which it cannot percolate, and then it fills the rocks to a level above which it overflows at the surface in springs or seeps (fig. 78).

The rocks at Philmont are already filled to the level of overflow, for there are hundreds of small springs on the sides and in the floors of valleys from the mountains to the plains. The rocks of Philmont are a vast, though leaky, subterranean reservoir. The top of this ground-water reservoir is known as the water table.

Philmont's springs are places where the water table meets the surface. As there are many springs in the high mountains at Philmont as well as on the plains, the water table is not very deep and is not flat—the word "table" is not very apt—but rather is shaped much like the land surface would be if the canyons were filled. The altitudes of springs show that the water table is highest in southwesternmost Philmont, where it is around 10,100 feet above sea level, and is lowest, about 6,400 feet, near Cimarron town. Its average northeastward slope is about 200 feet per mile; probably it does not slope evenly, but is flatter than this within the mountains and on the plains, and steeper across the mountain front. Water flows downhill whether above ground or below, so that ground water is flowing from the mountains to the plains.

How fast does this water travel? By comparison with streams, the ground water is moving down fairly steep slopes—somewhere between that of Cimarron Creek (70 feet per mile) and that of Cimarroncito Creek (250 feet per mile). Such slopes, though, do not mean that the water rushes along the water table like a mountain torrent; we know it does not, for the springs flow quietly. Rather, it means that ground water, to move at all, must have considerable fall to overcome the frictional resistance of the rock grains and narrow cracks through which it passes. The real rate of flow along the water table at Philmont is unknown.

Ground-water flow has been measured at a few other places by putting dyes or radioactive tracers at intake points and waiting until they show up in the water at springs or wells. In country having geology and climate similar to those of Philmont, an average drop of water may travel 50 feet a year, or a mile a century. Some of the fresh clear water you might drink from the springs on Wilson Mesa may have fallen on Baldy Mountain, 7 miles away, during the time of the Crusades. Most of it, no doubt, has had a less interesting history, having fallen more recently and much nearer.

The springs in most of Philmont issue only from porous sandstone and conglomerate, generally where they lie on shale, which acts as a water barrier because its pores are so narrow and poorly connected that water can scarcely move through them; or on dacite porphyry, a water barrier because it does not have any pores. Some of Philmont's intermittent springs may come from ground water trapped above the regional water table by local water barriers, such as shale beds. Such water bodies are thought of as "perched," and their tops are called perched water tables (one is shown in figure 78).

In southwestern Philmont most springs issue from the base of basalt sheets, which are water carriers because they are riddled with bubble holes and have cracks formed during cooling. The basalt sheets lie on gneiss and schist that have no pores. From this we realize that although all the rocks below the water table hold as much water as they can, they will not all yield water.

Wells may be thought of as artificial springs. At Philmont there are scores of wells, most of them on the low plains in Cimarron town and near the Scout camps, but some are on the high benches. Nearly all are less than 100 feet deep and draw their water from loose gravel or sand. Many more, drilled just as deep or deeper, have never yielded water or have run dry and been abandoned, showing that not every hole drilled through the water table will become a dependable producing well. Indeed, only wells that penetrate water-soaked rocks made of sand or gravel can be counted on at Philmont. Wells in igneous and metamorphic rocks produce if they happen to penetrate wide crack systems below the water table. Wells in shale, no matter how far below the water table, are dry; water will not pass through the narrow pores in this rock, and fractures cannot stay open because the rock is made mostly of soft clay.

After several especially dry years, some of the springs and wells in both the benchlands and plains have been known to become dry, showing that the water table has dropped. Even when there has been no general drought, some wells have gone dry because they were pumped faster than the ground water could flow to the well, artificially lowering the water table around the well intake. Indeed, some wells have gone dry without being pumped at all because the local water table has been lowered by overpumping at other wells nearby. Once the water table falls below the bottom of a well, the only quick solution is to deepen the well; for, as we have seen, the rate at which ground water flows back, or recharges, is very slow, even when plenty of water is available.

Every perennial stream at Philmont is partly fed by springs; otherwise, it could not flow in dry seasons. A perennial stream might even be defined as a place where the water table is consistently above a stream bed. If it is not, dry and flowing stretches may alternate.

You may have heard about or seen desert basins in which rivers descending from mountains vanish into the ground. This is no tall story or mirage in reverse; the Humboldt River in western Nevada is just one of many examples. The water table, which is above the river bed in the mountains, dips below the surface in the desert. Instead of ground water flowing off the water table into the river, it flows down the buried water table and either reappears miles downstream or remains in the basin until tapped by wells or by down-cutting streams.

The permanent natural lakes of Philmont are in places where the water table intersects the surface of a closed depression. If it did not, the water in the lakes would soon disappear by evaporation and by sinking into the ground. All the lakes and reservoirs on the dry lowland plains are manmade; the water table there is well below the surface. Because they are above the water table, they may disappear in dry years and, therefore, are not dependable water sources.

The combined water resources of streams, reservoirs, and shallow wells are able to fill the needs of the residents but are strained by the thousands of visitors during the hottest, driest months of the year. The permanent natural lakes, unfortunately, are too far from settlements to be of much use; besides, they are small. The number of summer visitors is increasing, and the water supply must be increased too. More reservoirs could be built, and evaporation from all standing water bodies could be greatly reduced by covering them with plastic film. More shallow wells could be drilled near camps. Whether efforts like this would repay the cost is uncertain. Perhaps new sources of water should be sought.

A possible new source is suggested by one small flowing artesian well that has been drilled into quartz sandstone near the mountain front at Ute Park. This particular well is of no use because it is not only feeble but is contaminated by marsh gas, but it raises an interesting question. Water can flow upward only if it is under pressure. Is it possible that large supplies of ground water under pressure exist deep beneath the plains of Philmont? Before considering this possibility, however, we must know more about the arrangement of the rocks beneath the surface, for special conditions are obviously needed to put ground water under pressure.

A CAKE OF MANY LAYERS
The rock sequence

We now have a fairly good idea of the different kinds of rocks of which Philmont is made. We have seen, too, that they do not appear at random but have an orderly arrangement: black shale, which is the main rock beneath the lowland plains, is less common in the benchlands and along the mountain front and is absent from the mountain core; yellow sandstone and coal appear only in the northern benchlands; lamprophyre is found only in the plains; gneiss, schist, and pink granodiorite are only in the mountain core; and so on.

After we looked over the landscape, we found it possible and interesting to put together observations about landforms into the model of plate 1. We could try to make a rock map on a topographic map by drawing lines around the stripes and patches of each rock type exposed, and giving each a special color or pattern. If we did this, however, we would not have much of a map, mainly because the outcrops of most of the individual rock types are so small that they could not be shown at the scale of our map or, for that matter, on a piece of paper 10 times larger. Even if we could make such a map, it would be of little use, for it would be wildly complicated and at the same time too simple; to put all the rocks of a particular kind together is to imply that they are related in time, which may or may not be true.

We will have to find a better way to show where the rocks are and how they are related to each other. We might consider putting 10,000 bulldozers to work stripping off broken rock, soil, and vegetation, so that we could see how the rocks are arranged. Besides being somewhat impractical, this would be of little help where the rocks have been partly removed by erosion. Plainly, we need to know something of the third dimension. One way would be to drill deep holes wherever our curiosity led us, but this would be even slower and more expensive than bulldozing. Fortunately, observation and common sense open easier ways.

The most important clue is that the sedimentary rocks of Philmont are piled up in a regular way. Suppose we consider the arrangement of rocks visible on the north side of Highway 64 from near Cimarron town westward.

The sequence of rocks at the mouth of Turkey Canyon, 3½ miles west of town, is shown in figure 79 and also in figure 3. The rocks fall naturally into four units that look flat from the highway but actually dip gently northward. Beneath the highest bench is yellow sandstone and conglomerate in a few thick layers separated by thinner layers of brown sandy shale. These alternating layers add up to a total thickness of perhaps 300 feet at the bench edge. A 10-foot-thick ledge of conglomerate is at the bottom. For convenience, let us call this sequence of beds unit 1.

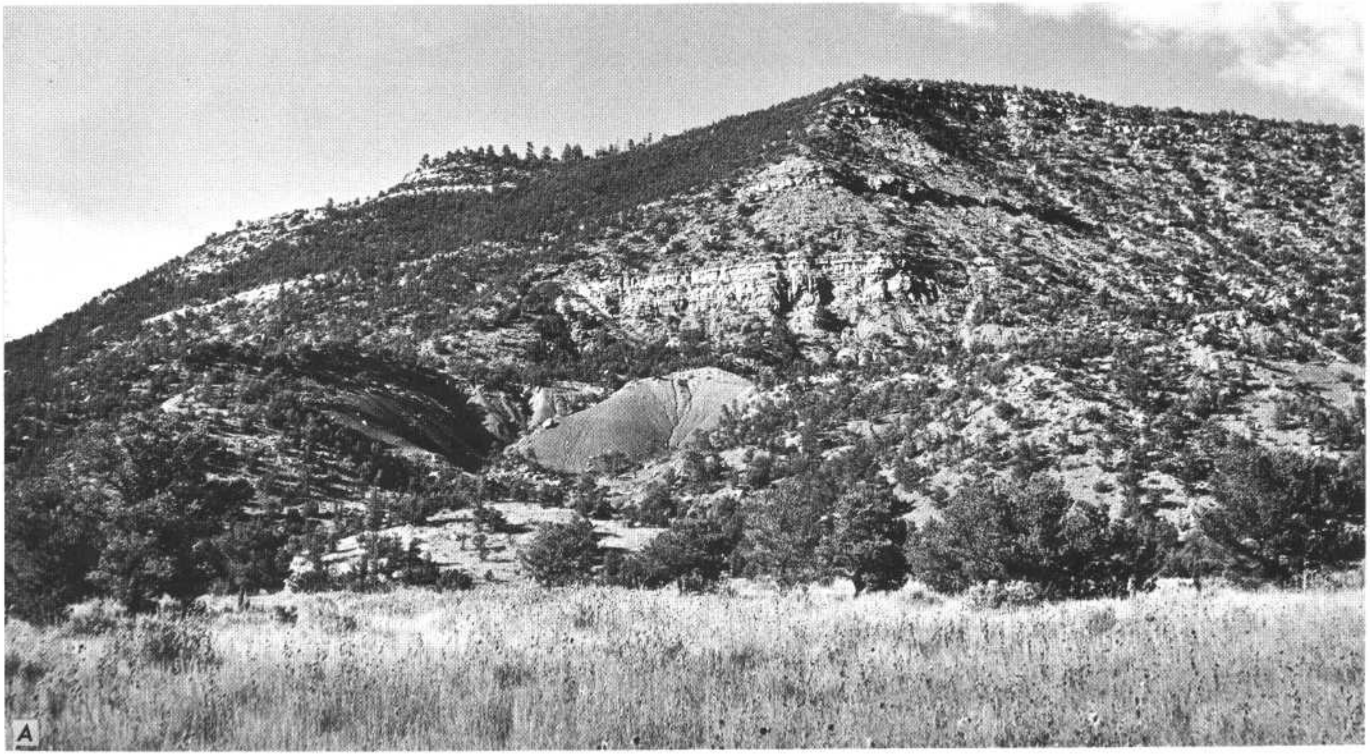
Beneath it are alternating much thinner layers of yellow and gray sandstone, black shale, and coal, each layer only a few feet thick. The whole sequence is about 150 feet thick and stands out from the rocks above and below; this will be unit 2.

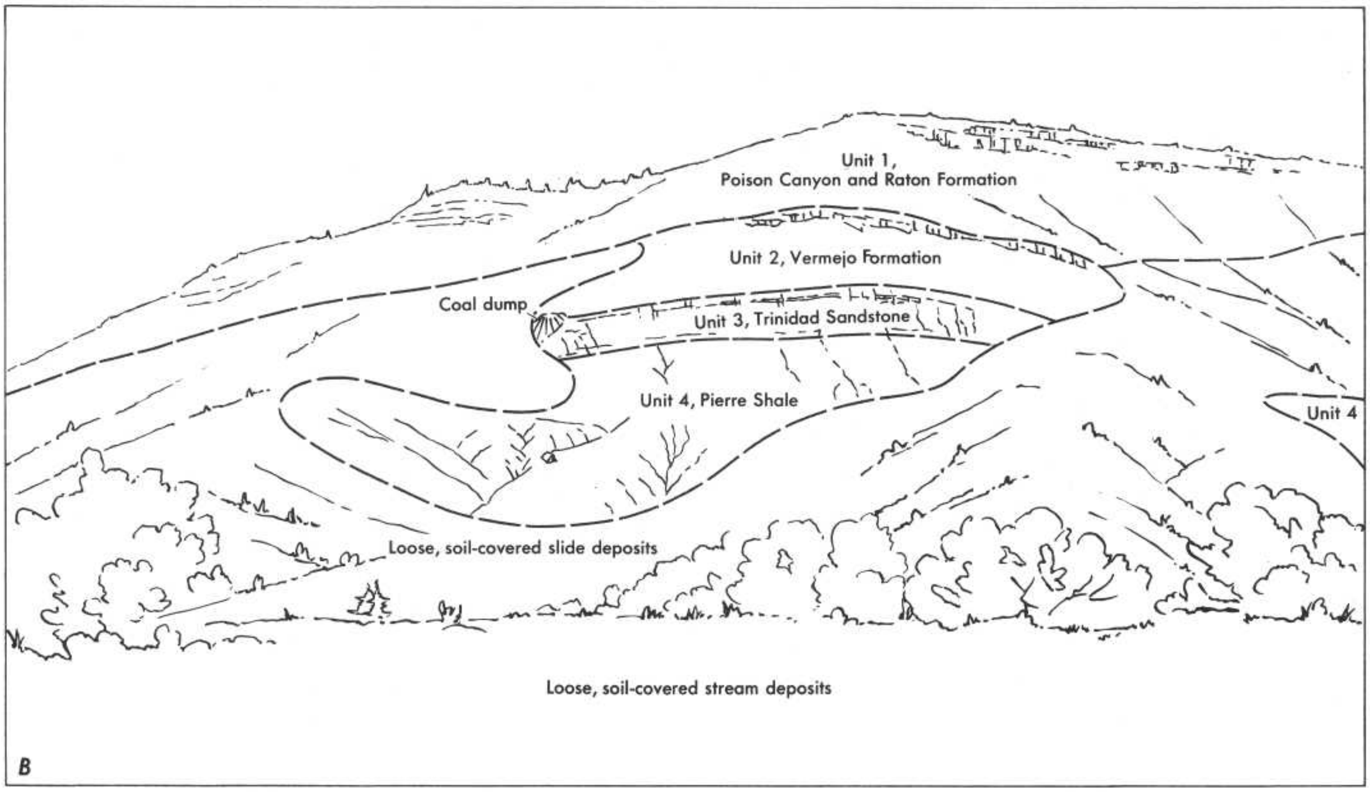
Still lower is a cliff of light-gray sandstone that has two dark layers—stained by dried oil—near the top. This sandstone sequence, about 100 feet thick, is unit 3.

Below the sandstone is black shale—unit 4. Only about 100 feet of this shale is exposed in the hillside near town; but the shale must be much thicker elsewhere, for it also appears beneath gravel in the creek bank on the south side of the road. We have no way of knowing, in this vicinity, how much thicker the shale body may be, because we cannot see the bottom of it.

Once we start thinking of rocks not as specimens or scenery but as huge layers, we realize that rock units continue beyond the bare outcrops beneath a mantle of soil, slide rock, and, near the creeks, of loose stream deposits; further, they once continued across what are now stream valleys.

Because the particles that make these rocks settled out of running or standing water, each lower bed had to be deposited before the bed above it. Unit 4 is the lowest, and





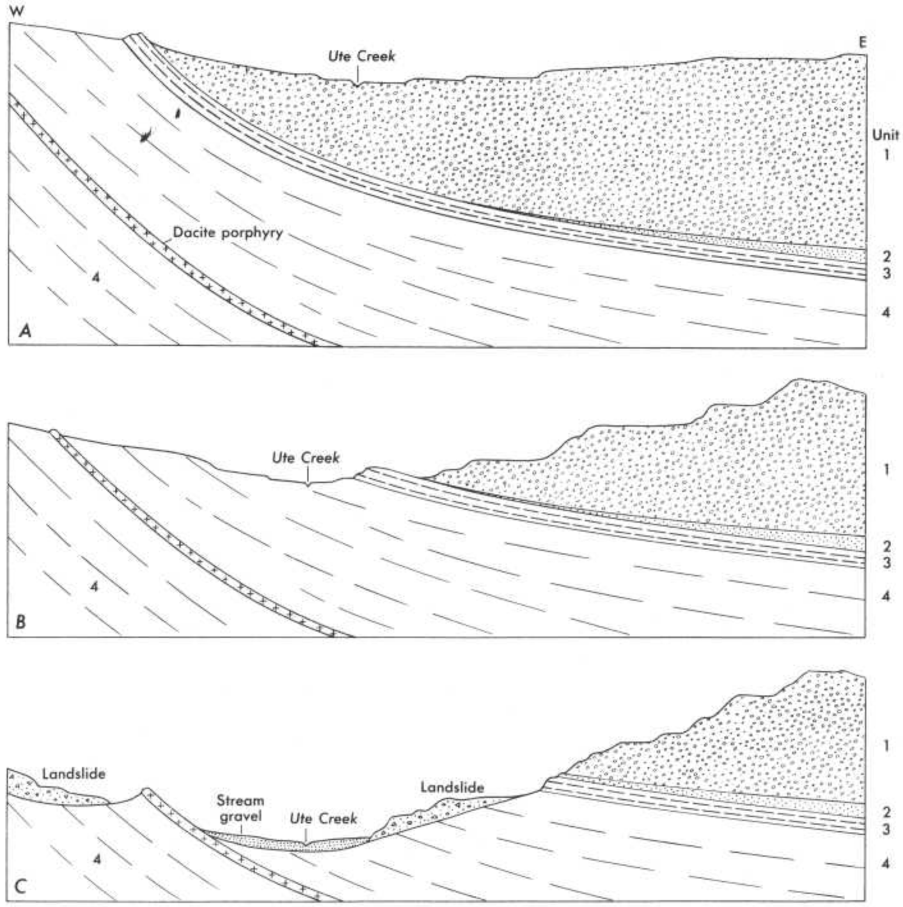
ROCK SEQUENCE on Cimarron Creek. Photograph (A) and sketch (B) of four rock units at mouth of Turkey Creek canyon, 3½ miles west of Cimarron town. (Fig. 79)

FOUR ROCK UNITS that crop out near Cimarron are still recognizable at the base of Midnight Mesa, 6½ miles west of town. (Fig. 80)

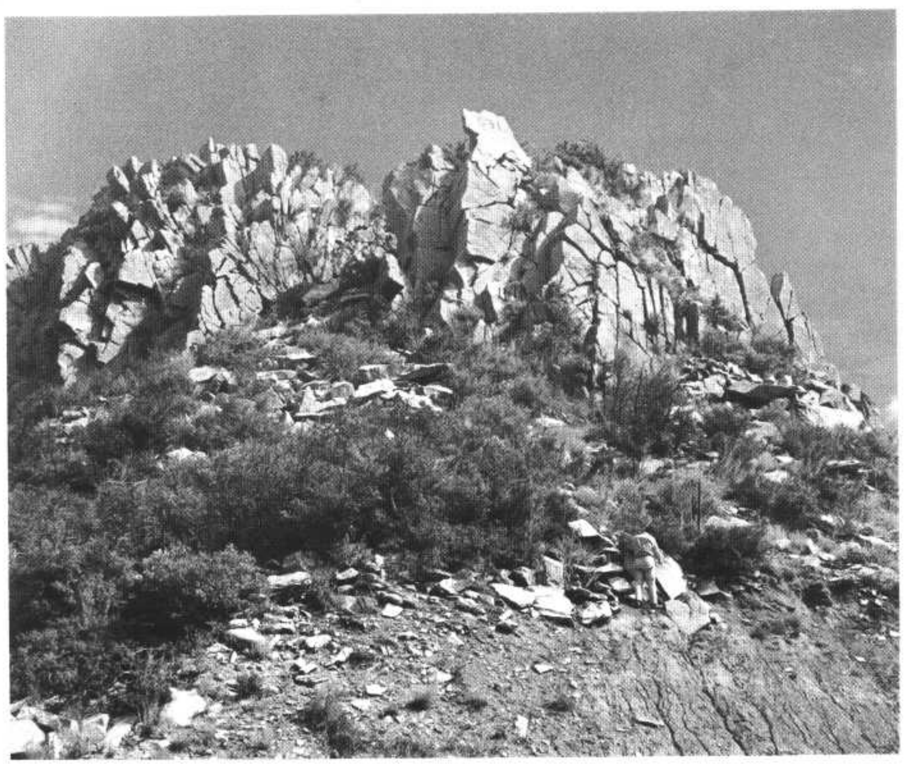
therefore the oldest, set of rocks in this exposure; and unit 1 is the highest, and therefore the youngest. This simple idea, that younger sedimentary rocks lie on older ones, is a basic principle in geology and is the main tool in working out the rock timetable. It is often called the principle of stratigraphic succession, or the law of superposition. It fits all rocks that form on the earth's surface—glacier deposits, sand dunes, volcanic ash falls, lava flows, and landslides, as well as waterlaid deposits.

The sequence stays about the same all the way up the lower canyons to Ute Creek valley; figure 80 shows the sequence at a point 6½ miles west of town. The sequence looks different opposite The Bench because the road rises above the top of the lower units for a little more than a mile, so that only yellow sandstone and conglomerate of unit 1 are visible at road level near Bear Canyon; but the lower units again are seen at the edge of Ute Creek valley, where they dip gently to the northeast. Going up the lower canyon, however, we begin to realize that unit 1 is far more than 300 feet thick; rather, it must be many hundreds of feet thick because it makes most of the high benchlands north of the canyon.

The rocks on the floor of Ute Valley are soil-covered landslides, except for some rounded gravel near Ute Creek. (See fig. 5.) (The road is on slide rock; Ute Creek, at the far left, is marked by a winding belt of trees.) These materials are lower on the land surface than the rocks of units 1–4 but do not really lie under them and are not older. Rather, they must be younger, for they were not formed until Ute Valley was cut down through the rocks of units 1–4 (fig. 81).



RELATIONS OF LANDSLIDES AND GRAVEL in the Ute Creek valley to other rock units. A, Before Ute Creek valley was cut by Ute Creek. B, Early stage in valley cutting. C, Ute Creek valley today. (Fig. 81)



DACITE PORPHYRY LEDGE above weathered outcrop of shale, part of unit 4 (Pierre Shale) near Ute Creek. (Fig. 82)

ROCK SEQUENCE on upper Cimarron Creek. Ledge of yellow quartz sandstone—upper part of unit 5 (Dakota Sandstone)—at mouth of upper canyon 0.3 mile west of Ute Park. Low outcrops of black shale of unit 4 (Graneros Shale) on the right (east) are concealed by vegetation. Light-colored rock at left edge is part of a dacite porphyry sheet. (Fig. 83)

Just west of Ute Creek is a bare ledge of dacite porphyry (fig. 82). Because the porphyry was not formed at the surface but was squeezed between layers as a melt, the rule of superposition does not apply, and we will not include the porphyry in our numbered sequence; but, at any rate, it is surely younger than the rocks into which it has been squeezed. At the west base of the porphyry ledge are outcrops of black shale, exactly like that of unit 4 on the east side of the valley a mile away but dipping more steeply eastward; clearly, the shale body of unit 4 is very thick, indeed.

From this point until we pass Ute Park, the only visible rocks on the north side of the road are young landslide and stream deposits and another bare ledge of dacite porphyry. But as we approach the upper canyon, still more black shale appears in a narrow belt; dipping eastward, the shale must be beneath the rocks we have been following. This black shale is like that of unit 4, which must be thousands of feet thick.

Now we enter the upper canyon (fig. 83), where great light-colored ledges loom on both sides. Four ledges are dacite porphyry, but two, separated by one of the dacite porphyry sheets, are of the yellow quartz sandstone that runs along the entire mountain front; one of these is shown in figure 83. These quartz sandstone ledges, each of which is about 50 feet thick, dip eastward beneath unit 4, and so must be older. Let the two sandstone ledges together be unit 5; its true thickness cannot be measured here because of the dacite sheets.

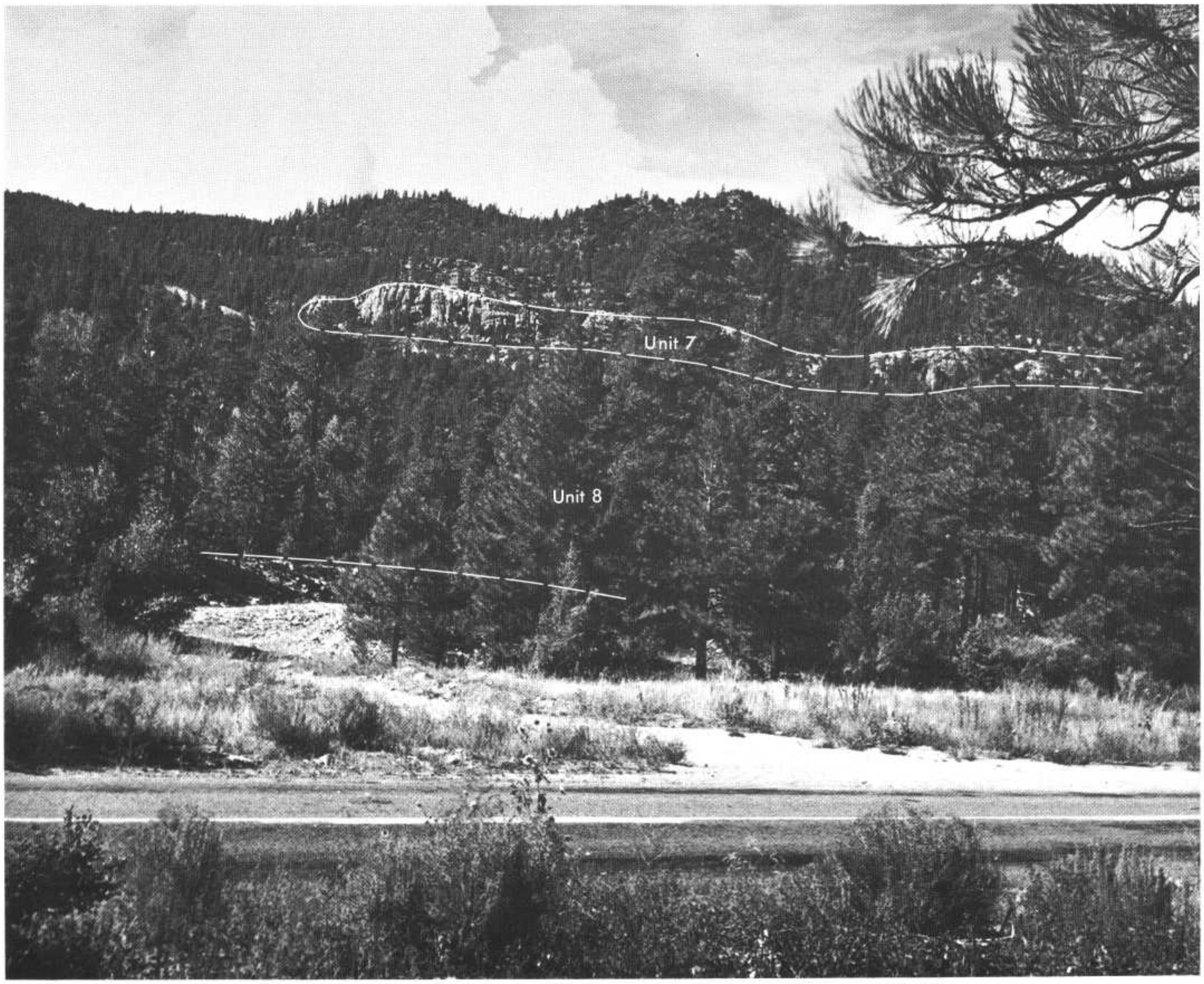
Half a mile farther west, after crossing the fourth ridge of dacite porphyry, and past the lower ledge of quartz sandstone of unit 5, we cross a grassy saddle broken by a few low outcrops of red shale and sandstone—unit 6—that dips eastward underneath unit 5. Because exposures are poor, the thickness of unit 6 is hard to measure; also, it is hard to see and is not shown in any of this group of photographs.

On the far (north) side of this saddle, and just above Gravel Pit Lakes, is another ledge of east-dipping yellow quartz sandstone—unit 7—much like that of unit 5 but only about 30 feet thick. Figure 84 shows this sandstone ledge a little west of Gravel Pit Lakes.

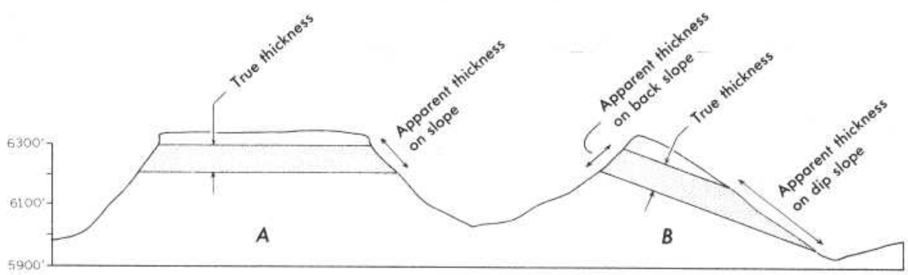
The lakes themselves are in young creek gravel, but between them and the light-colored ledge of unit 7 are scattered exposures of another body of red shale and sandstone—unit 8—that dips below unit 7. (See fig. 84.)

Beginning at the next ledge, dacite porphyry is exposed continuously for nearly a mile in the towering Palisades. (See fig. 54.)

Beyond the Palisades, to the west edge of our area at the Horseshoe mine (fig. 6), only metamorphic and igneous rocks crop out along the road. The metamorphic rocks are mainly



ROCK SEQUENCE on upper Cimarron Creek. Light-colored ledge of sandstone—unit 7 (Entrada Sandstone)—lying on red shale of unit 8 (Dockum Group), concealed by vegetation, in canyon wall west of Gravel Pit Lakes. (Fig. 84)



TRUE AND APPARENT THICKNESSES of rock units. A, In flat rocks, the true thickness of a unit is the vertical distance between the top and bottom. B, In dipping rocks, the true thickness can be found by drawing a diagram to scale or by using trigonometry. (Fig. 85)

mica schist but include some gneiss and quartzite. The igneous rocks are coarse-grained pink granodiorite (fig. 62) and dark pepper-and-salt diorite. The dip of layers in the metamorphic rocks is not parallel to the easterly dip of the sedimentary rocks but is nearly vertical. The red shale of unit 8 is not in contact with the metamorphic rocks along the highway, so that we cannot use superposition as a guide to their relative ages. Here, we do not need it. The schist and gneiss must be much older, for if any of the sedimentary units 1–8 had existed here when the metamorphism was going on, they, too, would have been metamorphosed.

An easy way to visualize the sequence of bedded rocks in this traverse up Cimarron Creek is to arrange the units in a vertical column, as though pushing together a spreadout hand of cards, and give each unit a pattern or color of its own and a thickness proportional to its observed thickness. For units that are flat or nearly so, the thickness can be measured directly by measuring the difference in altitude between the top and bottom; this can be done in many ways with instruments, or, on a good topographic map, by counting the contours and estimating the fractions of contours between top and bottom (fig. 85*A*).

For units that dip steeply, such as those west of Ute Creek, measuring thickness is more complicated. It is necessary to measure both the vertical distance between the top and bottom of a unit and the horizontal distance from top to bottom; measuring the slope distance from top to bottom gives the same result. Next, the amount of dip must be measured. After all these measurements are made, the thickness can be determined by trigonometry or, as in figure 85*B*, by using a simple diagram drawn to scale.

The rock sequence seen along Cimarron Canyon, with the thickness of each unit drawn to scale, is shown in the second column of figure 86. Traverses on several other roads and trails will show how regular the rock sequence is.

Take Ponil Creek, for example. Starting north up Ponil Creek from the Highway 64 junction, we recognize units 1, 2, 3, and 4 in the benchlands on either side of the wide valley. As on lower Cimarron Creek, only a little of unit 4 is visible near the valley floor, because it is mostly covered by soil and loose gravel. The same units are exposed for 3.5 miles. The abandoned coal mine of figure 49 is on the west side of the creek in this stretch; the coal is in unit 2. A little way upstream from Templeton Canyon, the shale of unit 4 dips beneath the valley, and only units 1, 2, and 3 are exposed. Just upstream from the mouth of Chase Canyon, the sandstone of unit 3 also dips beneath stream level, and only units 1 and 2 are visible in the canyon walls. Sandstone and coal from unit 2 are shown on figure 112.

At the mouth of North Ponil Creek, unit 2 dips beneath the surface, and from here to the edge of the map area Ponil Creek runs entirely in rocks of unit 1; figure 34 shows sandstone and conglomerate of unit 1 at Ponil Base Camp. Along Ponil Creek we can observe that, in this part of Philmont, unit 1 includes many layers of shale—some of them coaly—and much sandstone but very little of the conglomerate which is the main rock type in unit 1 farther west. The rock sequence along Ponil Creek is shown in the first column of figure 86.

Traveling west up the Cimarroncito Creek trail from the Philmont Scout Ranch Headquarters to the Lambert Mine Camp and on into the Red Hills, we pass through much the same sequence of rocks as we passed through going up Cimarron Creek. At the start of this journey, however, two more rock types are added to the sequence. One is rounded gravel that caps Horse Ridge. Lying on the black shale of unit 4, the gravel is younger than the shale but older than both the deposits of Cimarroncito Creek or the landslides at the base of Tooth of Time Ridge and Deer Lake Mesa; for the rounded gravel, like the solid rocks below, has been cut away to form the valleys in which the stream deposits and landslides lie. The other new rock type is the lamprophyre sheet of Horse Ridge, seen in figure 31. Though it is not a surface deposit, we can at least be sure that, because it cuts across the shale of unit 4, it is younger than unit 4 and all underlying units.

The sedimentary rock units 1, 2, and 3 of the Cimarron Creek sequence do not appear above the black shale on the Cimarroncito trail, but they form Antelope Mesa and Deer Lake Mesa to the north. As on lower Cimarron Creek, the beds dip gently northward. At the mountain front is Cathedral Rock, the first dacite porphyry ledge met on this journey. At its base is black shale of unit 4, which dips eastward and more steeply than the same rock on the plains, exactly as on Cimarron Creek at Ute Creek junction. Slide rock and young stream deposits cover the wooded valley that extends north from Cimarroncito Reservoir. In this valley is Cimarroncito Base Camp. On the west side of this valley, the creek cuts another, thinner sheet of dacite porphyry; exposes more black shale—still unit 4—in a narrow wooded valley; runs in a narrow canyon across a thick porphyry sheet for a quarter of a mile; and then meets the familiar double ridge of yellow quartz sandstone (unit 5), again separated by a porphyry sheet. Then comes the red shale and sandstone of unit 6, here, too, poorly exposed and also cut by a porphyry layer (fig. 87). The thin ledge of yellow quartz sandstone of unit 7 follows, and then the second red shale and sandstone, unit 8 (fig. 88).

Now we find sedimentary rocks older than unit 8 that were not seen on Cimarron Creek. For 0.7 mile upstream from the base of unit 8, the creek crosses coarse red and gray sandstone and conglomerate—unit 9 (fig. 86)—split by two sheets of porphyry. As on upper Cimarron Creek, all these layers dip rather steeply northeastward.

For the next mile, to and beyond Lambert Mine Camp, the creek runs in dacite porphyry. Then it is in gneiss and schist the rest of the way to its head in the Red Hills.

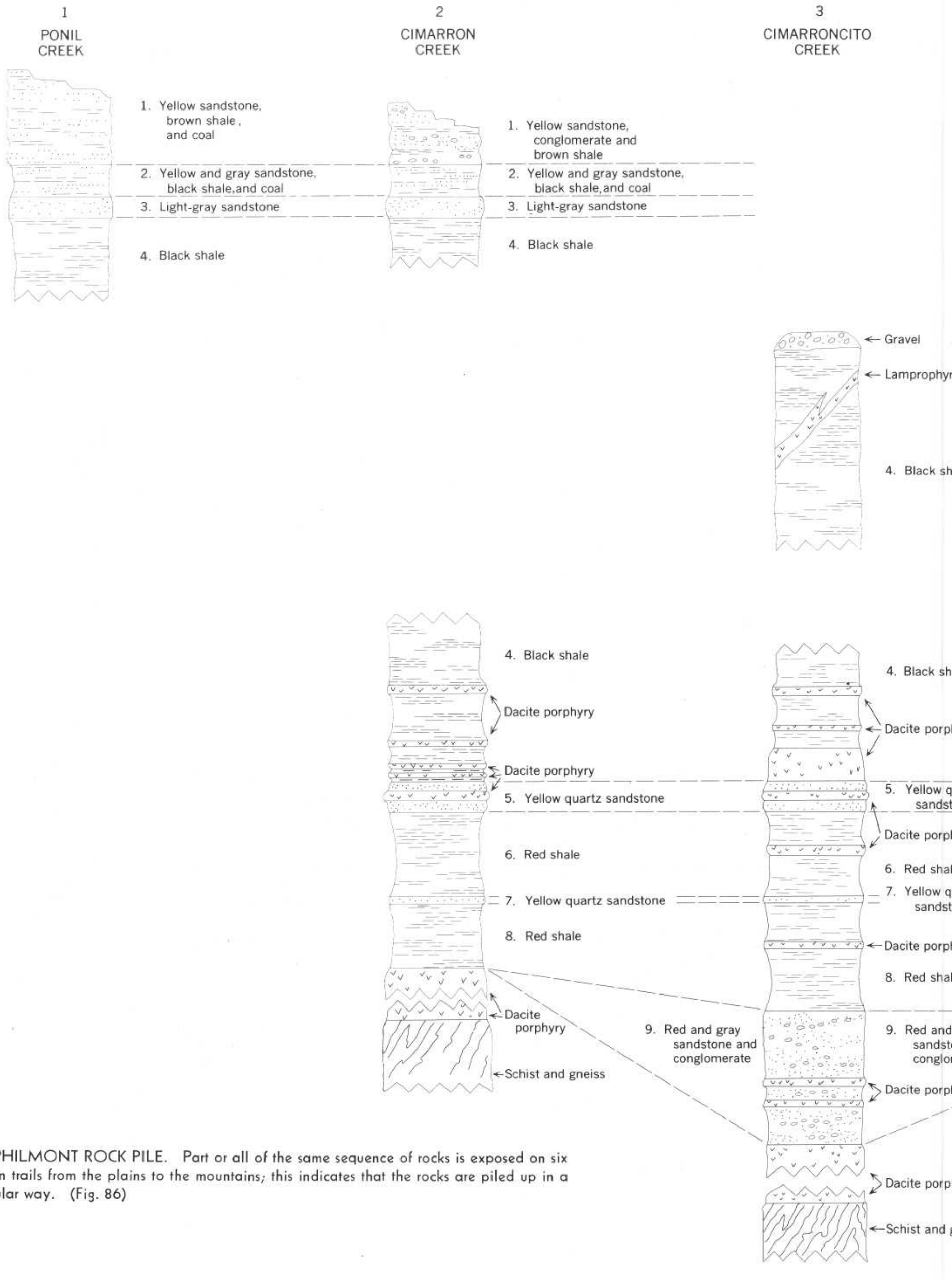
The sequence of rocks met in this traverse is shown in column 3 of figure 86. Two new units of sedimentary rock—unnumbered young gravel, and old unit 4, and one of igneous rocks—lamprophyre—have been added, but there has been no change in the order or in the general thickness of the units seen along Cimarron Canyon.

Practically the same sequence is repeated up the next main stream, South Fork Urraca Creek (column 4, fig. 86). Units 1–3 do not appear, but all the other numbered units do, and a few more. From the Camping Headquarters to the vicinity of the Stockade, the trail runs in young stream deposits on black shale (unit 4), which crops out here and there along the south side of the creek and around the small reservoir southeast of the Stockade. Then the trail and creek abruptly pass into 0.6 mile of canyon country, cut in a great mass of dacite porphyry.

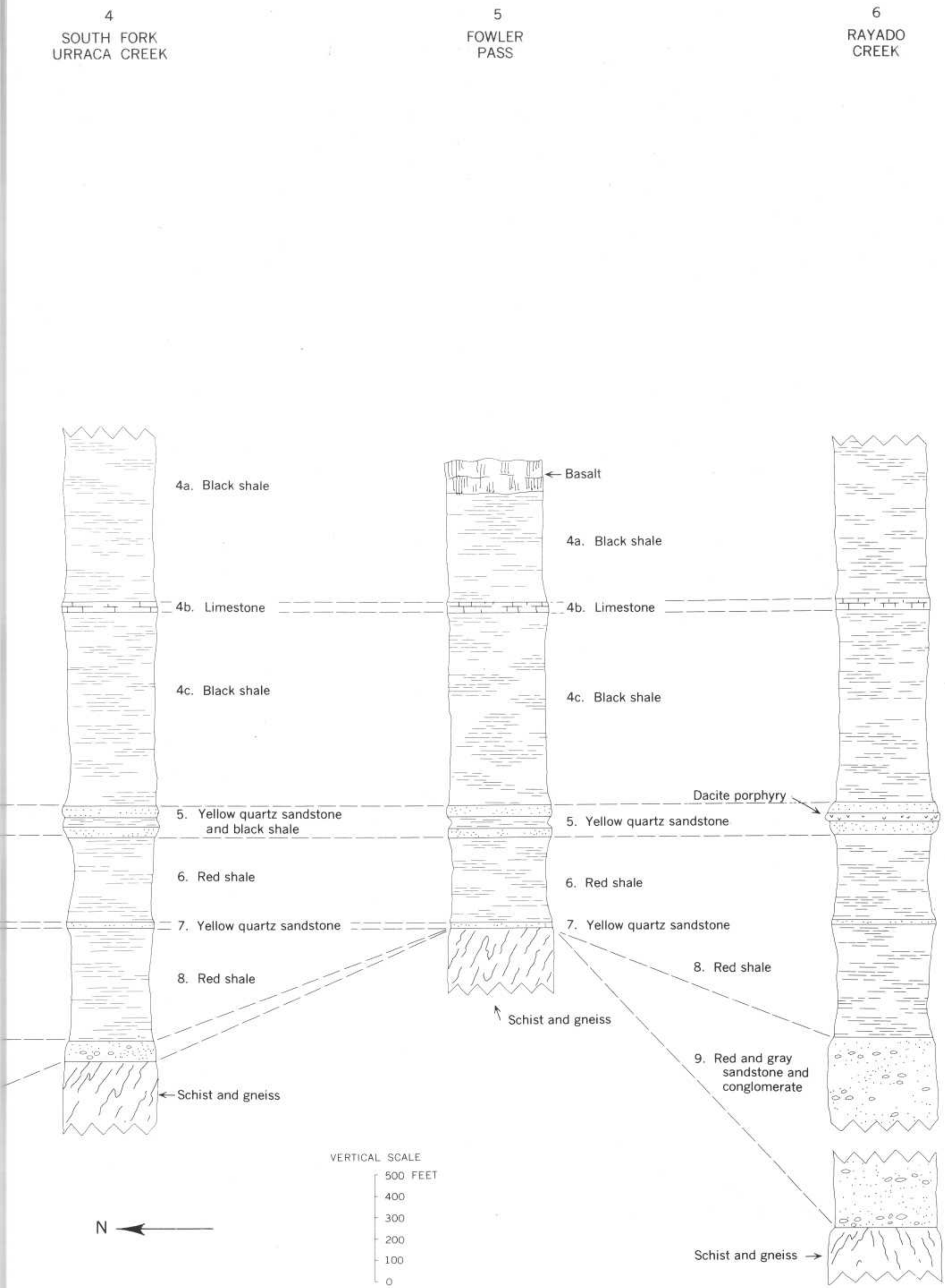
For the next 2 miles, all the way to the mountain front, the trail again crosses lowlands formed on landslide and stream deposits mantling unit 4, but a complication turns up in the simple picture of unit 4 as a vast body of black shale. Beginning near the turnoff to Stone Wall Pass and continuing 0.6 mile west, low ledges of limestone (shown in fig. 30*A*) crop out along the north side of the trail. Several ledges, each a few feet thick, separated by thin layers of black shale, add up to a limestone unit about 40 feet thick. Another change from the usual pattern is that the limestone dips rather steeply south, or toward the creek. Although outcrops are few, we realize that great thicknesses of shale lie both above and below the limestone unit, so that unit 4 now has three recognizable parts—an upper shale, 4a; a middle limestone, 4b; and a lower shale, 4c (fig. 86; and pl. 2).

At the mountain front the familiar sequence of sedimentary rocks reappears, but here there is little interruption by dacite porphyry. Units 5–9 are all present, but unit 9, which is hundreds of feet thick on Cimarroncito Creek, is less than 100 feet thick here. At first glance, all the other units below unit 5 seem much thinner, too, but this is only because they are standing nearly vertical, so that their width of outcrop is nearly their true thickness; beds that dip more gently have outcrops much wider than the true thickness. Unit 9 lies directly on gneiss and schist, without the intervening dacite porphyry that we met farther north. The trail remains in igneous and metamorphic rocks the rest of the way to Beaubien Camp and beyond. Exposed along the trail are pepper-and-salt diorite, diorite porphyry, and garnet schist, as well as the more common gneiss, mica and hornblende schist, and granodiorite.

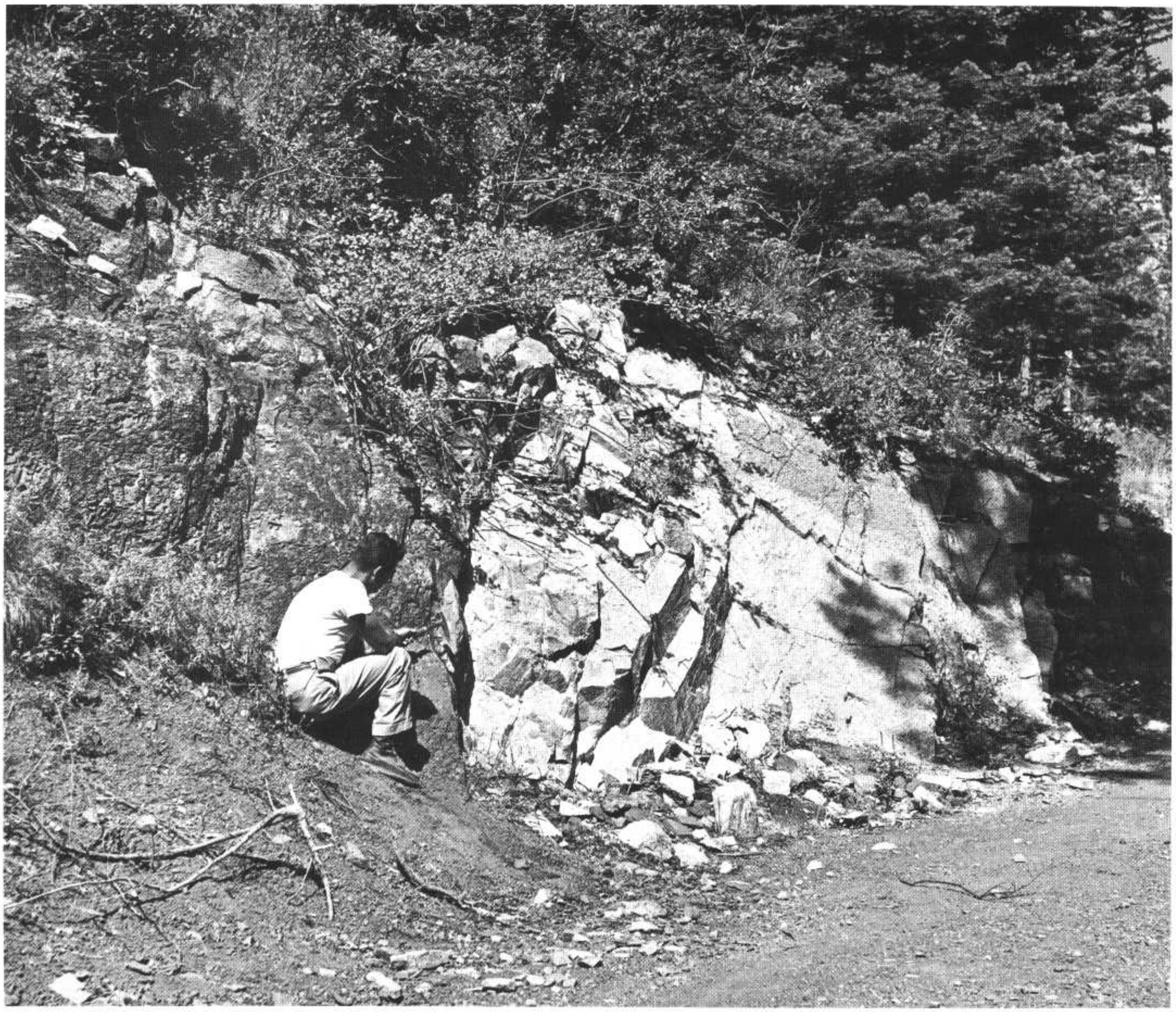
To include all the bedded rocks in this vicinity, we must retrace our steps to the limestone outcrops of unit 4b and travel westward to Crater Lake Base Camp and along the mountain-front trail to Fowler Pass (column 5, fig. 86). The camp itself is on landslide rocks. Above the base camp the trail starts climbing and crosses black shale, in the base of unit 4c, that dips eastward more steeply than the slope of the mountain front. As the trail climbs westward, it crosses lower and lower units. At the lowest switchback the trail passes on top of a magnificent ledge made by the upper quartz sandstone of unit 5 (shown in fig. 94). Then we cross the lower sandstone layer of unit 5, the red shale of



THE PHILMONT ROCK PILE. Part or all of the same sequence of rocks is exposed on six main trails from the plains to the mountains; this indicates that the rocks are piled up in a regular way. (Fig. 86)



4
SOUTH FORK
URRACA CREEK
5
FOWLER
PASS
6
RAYADO
CREEK
Basalt
4a. Black shale
4a. Black shale
4b. Limestone
4b. Limestone
4c. Black shale
4c. Black shale
Dacite porphyry
5. Yellow quartz sandstone
and black shale
5. Yellow quartz sandstone
6. Red shale
6. Red shale
7. Yellow quartz sandstone
7. Yellow quartz sandstone
8. Red shale
8. Red shale
Schist and gneiss
9. Red and gray
sandstone and
conglomerate
Schist and gneiss
Schist and gneiss
VERTICAL SCALE
500 FEET
400
300
200
100
0
N

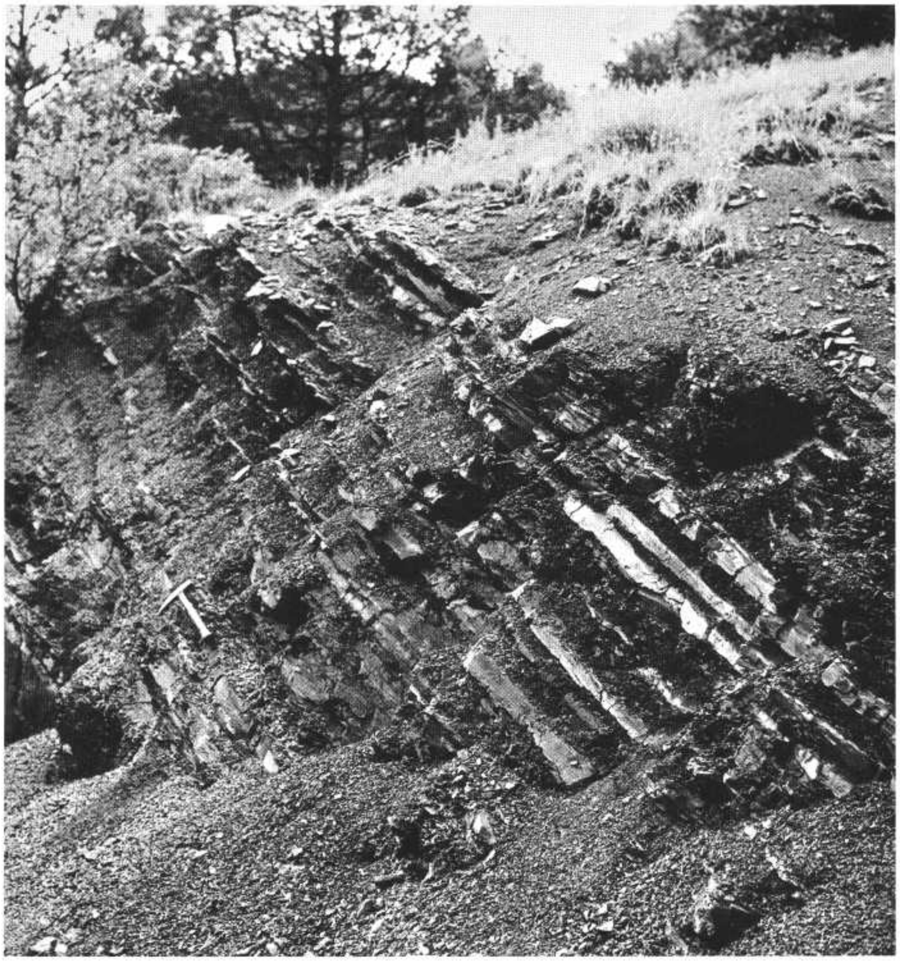


RED SHALE AND SANDSTONE OF UNIT 6 (Morrison Formation) on Cimarroncito Creek. Light-colored rock to right of man is dacite porphyry. (Fig. 87)

unit 6, and the thin yellow quartz sandstone of unit 7. But units 8 and 9 are missing—the trail passes abruptly, in the highest switchback, into gneiss and schist. The boundary between the metamorphic and the sedimentary rocks is roughly parallel to the trail, which turns and runs south for about a mile to the base of Fowler Mesa, so that the trail is now in gneiss and schist and now in quartz sandstone. The trail ascends Fowler Mesa by another series of steep switchbacks; here we see that not only units 8 and 9 but also units 6 and 7 are missing, and quartz sandstone of unit 5 is in contact with gneiss and schist.

On the upland surface at Fowler Pass itself, the trail is in gneiss and schist, mostly concealed by soil and vegetation; but just to the east, capping Fowler Mesa, is basalt. Although the basalt is an igneous rock, it flowed out on the surface and therefore can be regarded as part of the sequence of bedded rocks. It lies as an almost flat sheet across the upturned edges of units 4 and 5 and on gneiss and schist, so it is younger than all these. It must be older than the landslides, however, for we have already noticed that the slides flanking Fowler Mesa are made mainly of basalt chunks, surrounded by shale fragments.

Finally, a traverse up the southernmost of Philmont's large streams, Rayado Creek, repeats almost the entire sequence—units



RED SHALE AND SANDSTONE OF UNIT 8 (Dockum Group) on Cimarroncito Creek. (Fig. 88)

1–3 are missing, but units 8 and 9, missing near Fowler Pass (column 6, fig. 86), are present. All three subdivisions of unit 4 are well exposed, and the limestone of 4b crops out at the entrance to New Abreu Base Camp. (See fig. 30*B*.)

The two ledges of yellow quartz sandstone of unit 5, here again separated by a thin sheet of dacite porphyry, cross the creek about 3,000 feet above Old Abreu Lodge; and all the familiar units below it are present here, though some of them are hard to find because of the dense brush. The coarse red sandstone and conglomerate of unit 9 is very thick and can be seen dipping steeply in outcrops along the creek for 1¼ miles. The contact with gneiss and schist is below the saddle between Crater Peak and Rayado Peak.

We get a suggestion of what the rock sequence is like on the west side of the Cimarron Range by going up Agua Fria Creek, which branches west from Rayado Creek at Rayado Base Camp, and by crossing the crest of the range. Half a mile above Agua Fria Trail Camp, we leave gneiss and schist and pass onto the red rocks of unit 9, here dipping westward. These continue along the creek for 0.7 mile to where it rises to the rim of the Ocaté Mesa; there the sedimentary sequence is covered by basalt. Continuing across the Mesa and down West Agua Fria Creek, on the west side of the Cimarron Range, we cross units 8, 7, and 6, in that order, all dipping west. Clearly, the range is a great arch over which many, if not all, of the nine units of solid sedimentary rocks were once continuous.

So, by using the simple idea that in bedded rocks any layer is younger than the layers beneath it and older than the layers above it—the principle of superposition—we have been able to recognize the same rock sequence throughout the Philmont region. We also are beginning to get some ideas about the structure of the rock bodies.

We may think of the rocks of the Philmont area as a huge layer cake. It has, however, been baked by a careless baker, as the layers are not neatly shaped or arranged. Almost every layer changes in thickness and in other details from place to place, some within inches, others in miles; many thin to nothing within Philmont. Others disappear by gradually passing into a different type of rock. For example, a single bed may be a pebble conglomerate near a source of pebbles, shale miles away, and sandstone in between. The layers change in the same way from top to bottom. Many have distinct tops and bottoms, whereas others pass gradually above and below into other rocks. But despite all the changes and irregularities, there is no mistaking an overall orderliness of the rock strata.

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PUTTING THE ROCKS ON PAPER

Naming and mapping formations

Now we have a practical way to put on paper what we have seen on the ground. We can make a rock map by tracing across country the units recognized in the canyon traverses, for these units are large enough to show on a small piece of paper.

We have 20 units to work with. The 9 units of solid sedimentary rocks noted in our traverses make 12 map units, as unit 4 has three parts and unit 1 can be split into two intertonguing units—a western one of coarse sandstone and conglomerate, and an eastern one of finer grained rocks, including much shale and a little coal. Older than all of these are two units, the granodiorite and the metamorphic rocks. Younger than the solid sedimentary rocks are six units. Three are igneous rocks: (1) sheets and irregular masses that formed below the surface, including dacite porphyry, diorite, andesite, and lamprophyre; (2) basalt lava; and (3) volcanic bomb beds and other crater rocks. The other three are loose sedimentary rocks: (4) sand and gravel on benches; (5) landslides; and (6) sand and gravel on valley floors. By pooling the information in the columns of figure 86, we can show all 20 units in a single column—plate 2, in the back pocket—that summarizes the rock sequence.

A geologic map has been made by tracing these units, or formations, throughout Philmont on a topographic map, used as a base. It is plate 3, which also is in the back pocket. If you are visiting the area, it might be impractical to take along this book, but you may find it stimulating to take along the geologic map.

Nature makes rocks; geologists invent formations to make the rocks mappable. It is worthwhile to learn a little about this basic working tool. Formations are practical units that are thick enough and cover enough area to show at the scale of mapping but, if possible, are thin enough so that there will be several on the map. A formation may be mainly a single kind of rock like the cliff-making gray sandstone of unit 3, named Trinidad Sandstone in figure 86 and on the geologic map (pl. 3), where the name includes the rock type; or it may consist of a series of layers of two or more kinds of rock that are related in origin, like the thinly interbedded lowland deposits of sandstone, shale, and coal of unit 2, above the Trinidad Sandstone, named Vermejo Formation.

Sometimes it is useful to separate an established formation into parts or members; thus the thin limestone of unit 4b is the Fort Hays Limestone Member of the Niobrara Formation. On the other hand, it is sometimes impractical to map established formations. Thus unit 4a, referred to here simply as the Pierre Shale, actually combines two sequences of similar rocks: the shale part of the Niobrara Formation (bottom) and the Pierre Shale (top), which are mapped separately elsewhere. Unit 4c combines three—the Graneros Shale (bottom), Greenhorn Limestone (middle), and Carlile Shale (top)—because there was no time to find and map the very thin Greenhorn Limestone; without the Greenhorn, the two shales, which look alike, cannot be separated. Also, two or more formations that have a lot in common are sometimes combined in a group; thus, unit 8, called Dockum Group, is divided elsewhere into the Santa Rosa Sandstone (bottom) and the Chinle Formation (top).

Twelve of the formations at Philmont, or all the solid sedimentary rocks, have been given names, as a practical way to identify and remember them; they are referred to by these names on plate 2, on the geologic map (pl. 3), and from here on. A formation is usually named for a geographic feature—a city, a river, a mountain, a county—near which it is well exposed or, commonly, was first mapped. The formations at Philmont draw most of their names from nearby New Mexico and Colorado—Poison Canyon, Raton, Vermejo Creek, Trinidad, Sangre de Cristo Mountains—but the Fort Hays Limestone Member was named for Fort Hays, Kansas, 270 miles away; the Pierre Shale, for Pierre, South Dakota, 600 miles away; and the Entrada Sandstone, for Entrada Point, Utah, 400 miles away.

No new formation names are used in this book. Several names, such as Dakota and Pierre, have been used for a hundred years; all the others have been in use since early in the century. But this does not mean that the rocks of the United States were all satisfactorily named long ago: fewer than 2,000 names had been applied to American rocks by 1900, but something like 10,000 were added by 1936, and more than 5,000 additional names were coined between 1936 and 1955!

Most of these names are for sedimentary and volcanic rocks, but several thousand are applied to metamorphic and intrusive igneous rocks. This does not mean that the rock column of the United States is so thick and varied that it takes many thousands of named formations to describe it. Rather, it shows how often cautious gologists have given the same rocks different local names because the rocks have not been traced between areas and the identity is not sure. The country is so large and so much of its geology has not been mapped in any detail that rocks of what may someday be called by one name now have as many as 50 local names. The rocks may be dead, but the task of describing, interpreting, naming, and relating them to each other is still very much alive!

At Philmont we confidently use names that were first used far away, because the formations have been traced across country by following the outcrops or by drilling. To name formations in this way is practical as well as convenient. The relation of local rocks and the events that made them to neighboring rocks and events is learned by following recognized formations across country. This may merely satisfy curiosity, or it may be of economic value. If a certain formation, for example, has yielded oil or coal or uranium in one area, it makes sense to prospect it carefully elsewhere.

That some formations can be traced over hundreds or thousands of square miles gives an idea of the extent of certain individual rock layers laid down on the floors of ancient oceans or on the broad flood plains of vanished rivers. It also suggests why we have not bothered to name the bedded rocks of small extent, such as the landslide aprons, the gravel and sand caps of the plains and valleys, or the basalt flows, even though they may be a large part of the local geology.

We can also place the intrusive igneous rocks on plate 2 because we know the relation of some of them to dated sedimentary rocks—they must be younger than sedimentary rocks they cut and older than sedimentary rocks that lie on their eroded surfaces—and because we assume that in an area the size of Philmont all the intrusive rocks that look alike and are of similar composition are of the same age, if there is no positive evidence to the contrary.

Formation names are not given to the igneous rocks, though this is often done elsewhere, because it would serve no useful purpose here. We cannot relate them to other igneous rocks beyond Philmont and do not need formal names for them in this book.

WHEN WAS THIS CAKE MADE?

The rocks are now arranged in the order of their relative ages, but what are their ages in years? If earth processes went on in the past at about the same creeping rate as they do now, vast stretches of time were needed to accumulate the many thousands of feet of rocks piled up here, to alternately submerge the area beneath the sea and raise it to mountainous heights, and then to carve the mountains away. Much time was needed, but how much? One way to get at this would be to measure the rates at which sediments like those of Philmont are now piling up on land and sea, and the rates at which mountains like the Cimarron Range are now rising—if they are—and at the same time being worn down. This plan sounds good, but it is beset with difficulties, mainly because not enough measurements have been made in enough places for a long enough time to serve as reliable yardsticks.

Far better than a theoretical yardstick is a natural clock built into certain rocks: radioactivity. A few elements continuously throw off particles from their nuclei and break down into simpler elements at a uniform rate that is not changed by heat, pressure, chemical conditions, or time. If we know the rate of breakdown, we can figure out how much time has passed since breakdown began by comparing the amount of the remaining original element with the amount of its disintegration products. These days almost everyone is familiar with the fantastically rapid disintegration rates, measured in fractions of a second, of elements such as plutonium that are used in atomic bombs and nuclear power plants. Rapid disintegrations of this sort are not of much use in dating rocks, but some elements disintegrate so slowly that measurable amounts of the original element remain after many millions of years.

Uranium is the most useful of these elements, for it is widespread though not very abundant, and 6,700 million years must pass for half of a given amount to disintegrate, mainly to lead, helium, and electrons. By comparing amounts of either lead and uranium or helium and uranium in unweathered specimens, we can determine the number of years since the uranium-bearing mineral became solid. Unfortunately, this can be done only with uranium minerals that crystallized from a melt. In a sedimentary rock there is no way of knowing how much of the lead in a sample is the product of disintegration of nearby uranium and how much was simply washed in with uranium.

Like uranium, the elements thorium, potassium, and rubidium are also radioactive and have extremely slow breakdown rates. They are also used in similar ways to date rocks.

Unfortunately, radioactive dating with these elements is terribly slow, difficult, and expensive, and requires absolutely unweathered material, so that only a handful of rocks have yet been reliably dated in this way. The oldest rock now dated by radioactivity in the United States—gneiss from Minnesota—is more than 3 billion years old.

Because of their slow rates of breakdown, elements like uranium, thorium, potassium, and rubidium are most useful in dating rocks that are hundreds of millions of years old. In younger rocks these elements have disintegrated so little that it is hard to collect enough material to make a good analysis.

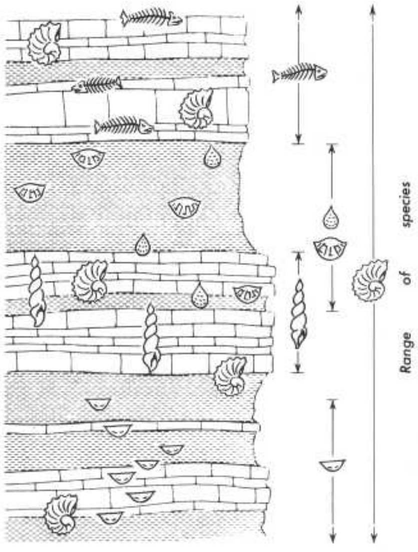
Some sedimentary rocks that contain organic material, if they are less than about 50,000 years old, can be dated by a radioactive form of carbon. This carbon (carbon 14) is formed by cosmic-ray bombardment and is absorbed by all living things and buried with them at death. It is preserved best in shellfish and trees. It breaks down so rapidly that half of any initial amount will disappear in 5,600 years.

Unfortunately, no radioactivity age determinations have been made of any rocks from Philmont. Crude limits on the clock age of the oldest rocks at Philmont—the gneiss and schist of the mountain core—can nevertheless be set in an indirect way. The gneiss and schist are near the south end of a belt of similar rocks that stretches for more than 500 miles along the Rocky Mountain front, from northeastern New Mexico to central Wyoming. Many radioactivity measurements have been made of the age of granite and pegmatite that cut these metamorphic rocks in central Colorado. Most of them range from 900 million to 1,500 million years. The metamorphic rocks must be still older.

The oldest rocks at Philmont, then, are probably more than 900 million years old. The youngest are still forming. Without any radioactivity dates, how do we get at the ages of those between?

Fossils—raisins in the rock cake—come to our rescue. Let's see how they are used. Animals and plants live and die almost everywhere on the land and in the sea. At death, the great majority of organisms simply vanish by being eaten, by completely decaying, or by being broken into unidentifiably small bits. Of those uncountable billions of animal and plant individuals living and dying, only a tiny fraction need be buried to preserve rich evidence of past life. If the evidence is enough to tell something about the appearance or habits of a former animal or plant, it is a fossil (from the Latin for "something dug up") It may be a hard part such as a shell or bone buried and preserved without change. Most often it is a part that has been partly or wholly altered by decay and by the action of percolating water but has retained its organic form. Some fossils are merely prints or impressions made in soft sediments that later hardened; soft thin organisms—worms, leaves, jellyfish—are most often fossilized in this way. Such indirect evidence of life as tracks, footprints, burrows, borings, and excretions may be preserved in one way or another and also serve as fossils. Some of the ways in which fossils are preserved were illustrated in the chapter on rocks.

The assortment of fossils in each formation is not haphazard but is distinctive, and most fossil species have a limited range: they appear in a particular layer or formation or in several successive formations and then disappear (fig. 89).



FOSSILS and formations. (Fig. 89)

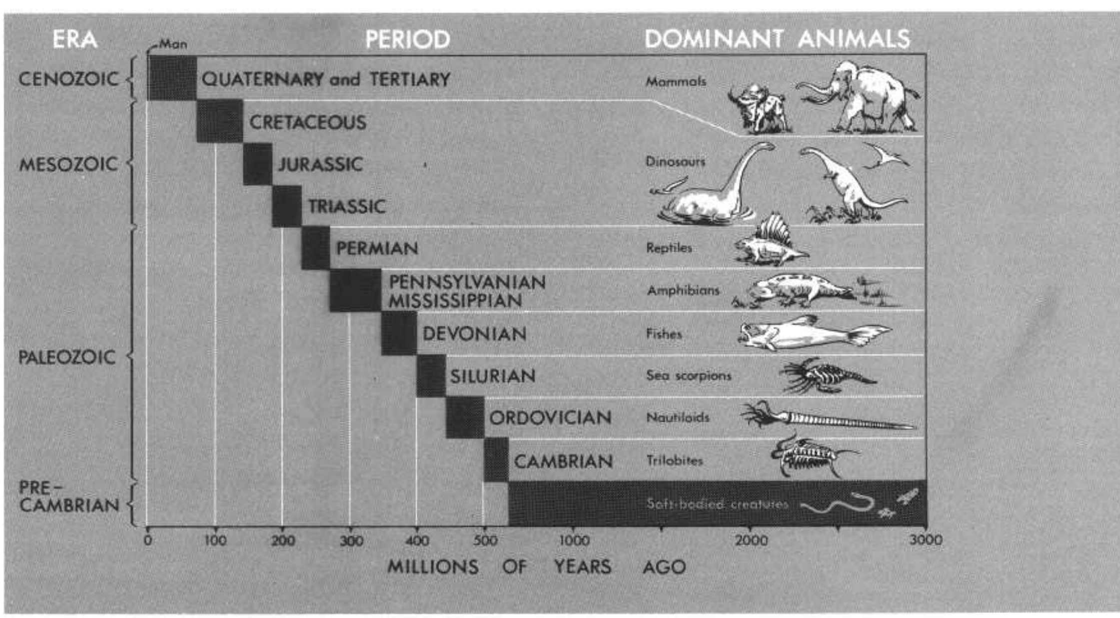
Once a species disappears—that is, when it becomes extinct—it is gone forever, never to recur in younger rocks. Thus, rocks having the same distinctive sets of animal remains—called faunas—or of plant remains—called floras—are of about the same age wherever they occur, even if at opposite sides of the earth. These ideas about fossils are now more than 150 years old and are supported by thousands of carefully located collections from all over the world.

Using fossils as tools, we are able to decide the relative ages of rocks anywhere that contain enough of them and to devise a worldwide scheme for expressing relative age, as well as for breaking geologic time into convenient units. The standard geologic time scale is shown in the chart below.

From the fossil sequence it is clear not only that fossils trapped in rocks of different ages are different from each other but that their variety and complexity increases toward the present. The younger a fossil fauna or flora is, the more it is like living communities.

The early geologists who made the geologic time scale had this in mind when they named the major divisions or eras—each name ended in "-zoic," from the Greek word for life. Three of the four eras now used retain these names: Paleozoic (ancient life), Mesozoic (middle life), and Cenozoic (recent life).

GEOLOGIC TIME CHART



Few fossil species in the Paleozoic rocks closely resemble any living plant or animal. In early Paleozoic time there were no land plants or animals—at least their remains have never been found in flood-plain and near-shore rocks of that time. The fossils in the lower Paleozoic salt-water rocks are remains of extinct species of such plants and animals as primitive shellfish that lacked backbones, structures like coral reefs built by algaelike plants, and markings made by worms. Land-plant and animal remains as well as salt-water fish appear first in middle Paleozoic rocks. Birds do not appear in the rocks until early Mesozoic time; and mammals, not until the end of Mesozoic time. Dinosaurs first lived in early Mesozoic time and were extinct by the end of the Mesozoic, whereas the remains of manlike creatures are not found in rocks older than late Cenozoic, so that no man ever saw a live dinosaur, contrary to the comic strips. Most living plant and animal species are only a little older than man.

Each of the three life-rich era is divided into periods, 12 in all, as shown in the chart on p. 93. This is enough subdivision for our purposes though the periods have all been split further into epochs, and some epochs have also been split.

The names of the periods make a motley list. Eight of them are derived, like modern formation names, from places in which rocks of that age are well exposed and were early studied. The early geologists who chose them, however, were not overly concerned with words and bothered little about uniform usage. Cambrian, for example, comes from Cambria, an ancient name for Wales, and Permian comes from the province of Perm in Russia; but Cretaceous refers to the fact that rocks of this age in Britain are mostly chalk, which, in Latin, is *creta*. (As it happens, very few rocks of Cretaceous age elsewhere in the world are made of chalk; so that this is a very good reason for avoiding descriptive names for time units.) Triassic comes from the fact that rocks of this age, where first studied in Germany, were in three distinct formations. The two periods of the Cenozoic are relics of an early attempt to subdivide geologic time into four great episodes: Primary, Secondary, Tertiary, and Quaternary. This attempt was abandoned long ago, but the two youngest names remain.

Cambrian rocks are the oldest rocks that have abundant fossil remains useful for dating. Beneath them in many parts of the world are great thicknesses of rocks that lack distinctive fossils, and these rocks are now lumped together simply as Precambrian. Eventually, when better methods of dating are discovered, the Precambrian Era, like the other eras, will be subdivided into periods and epochs.

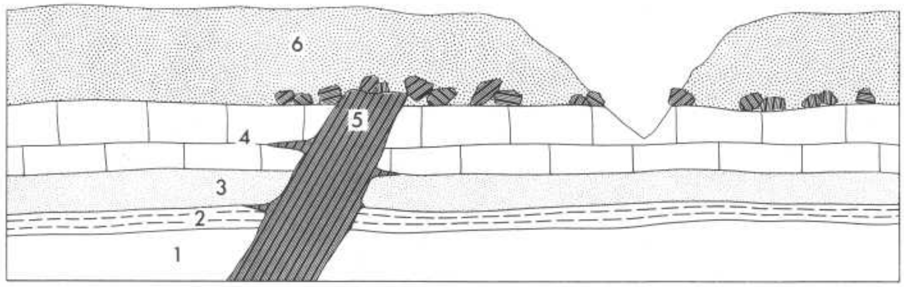
The world-wide geologic time scale is a remarkable achievement of men acting cooperatively, but it is still only a guide to relative age. And, as clock age can be determined from radioactivity only in igneous rocks, which rarely have any fossils, we might seem to have reached the end of the dating line. Fortunately, it is often possible to determine the *relative* ages of particular igneous and sedimentary rocks. If the clock ages of the igneous rocks are determined by radioactivity and the geologic ages of the sedimentary rocks by fossils (or by relations to other sedimentary rocks), then the two sets of ages can be put together to determine the clock ages of the sedimentary rocks and the geologic ages of the igneous rocks.

Deciding the age relations between igneous and sedimentary rocks is often even simpler than finding the relative ages of sedimentary rocks alone. Those igneous rocks that are deposited on the earth's surface—flows of lava and falls of volcanic debris—can be treated like sedimentary rocks: they are younger than the rocks beneath them and older than those above. Of course, the idea of superposition is of no use for dating the intrusive igneous rocks, but there are other ways to learn their relative ages: intrusive rocks are younger than any rock they intrude, older than any rock that is deposited on top of them after they have been exposed, and older than any sedimentary rock that contains fragments eroded from them, even if the two rock bodies are not actually in contact (fig. 90).

Suppose, for example, that a limestone formation containing Devonian fossils lies on a lava flow and is overlain by a conglomerate formation containing Mississippian fossils; the lava and limestone are cut and baked by an intrusion of pink granite that ends abruptly at the base of the conglomerate, which has pebbles of pink granite. This situation is sketched in figure 91.
If the lava has a radioactivity age of 400 million years and the granite, 350 million years, it seems safe to conclude that the Devonian formation (which may represent only a fraction of the entire Devonian Period) is between 350 and 400 million years old.

By weaving together the handful of really reliable clock-age determinations that have been made and the geologic ages of associated rocks, it is possible to give some crude estimates of the length, in years, of the geologic periods and eras. These are given in the chart on page 93. The technique of radioactivity age measurement is young and is rapidly being developed. By the time this book is in print, some of the numbers in the chart will no doubt already be obsolete. At any rate, they give us a fair idea of the vastness of earth time as well as confirmation of the fossil succession and of the geologic time scale. They also show that the periods based on fossils are of very unequal length, and become progressively shorter as they come nearer the present. This is not at all surprising: as with human history, the more recent an event, the better, more nearly complete, and, therefore, more detailed the record.

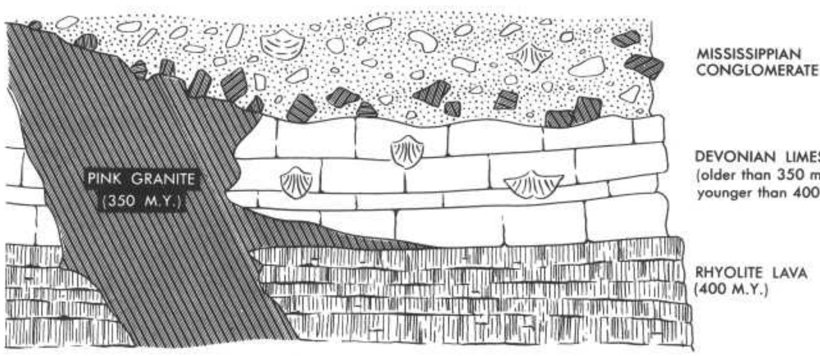
At last we can make some educated guesses about the ages, both geologic and clock, of Philmont rocks. Starting at the bottom, the metamorphic rocks are not merely older than the Sangre de Cristo Formation but are almost certainly of Precambrian age. From this we should not leap to the conclusion that metamorphic rocks everywhere are Precambrian. The "ancient" look of gneiss and schist may be very misleading. This has been proved by tracing fossil-bearing sedimentary rocks directly into areas where the same rocks are metamorphosed; even more dramatic are the few but remarkable discoveries of identifiable, though distorted, fossils in highly metamorphosed rocks. Metamorphic rocks like those at Philmont are known to be as young as Cretaceous in other parts of the United States—such as the Sierra Nevada of California—and of early Tertiary age in the French Alps, the Himalaya Mountains, and the Dutch East Indies. That no younger gneiss or schist is known probably means that erosion has not yet exposed such rocks rather than that metamorphic conditions have not existed deep below the surface in more recent time.



DATING INTRUSIVE IGNEOUS ROCKS. The age of an intrusive igneous rock can sometimes be read from its relation to other rocks. In this example, sedimentary formations 1, 2, 3, and 4 were deposited. Then they were intruded by a sheet of dacite porphyry (5). These rocks were eroded and, later, sandstone formation 6, containing pebbles of dacite porphyry, was deposited. The dacite is therefore younger than formations 1–4 and older than 6. Even if the dacite sheet itself is buried, fragments from it seen in the base of formation 6 (in the valley at right) are enough to date it. (Fig. 90)

All the named formations but the Entrada have enough fossils in, or not far from, Philmont to set their geologic ages, which are shown opposite the formation names on plate 2. Along with the geologic ages on plate 2 are estimates of clock ages from the chart on page 93. Together, these two kinds of ages tell much more about the history of Philmont than we could ever have learned from the most careful study of the rocks simply as rocks. For example, the clock ages in the chart make very plain the time gap—more, perhaps vastly more, than 700 million years—between the metamorphism of the gneiss and schist deep beneath the surface and the exposure of these rocks to provide part of the load of the sluggish streams that laid down the Sangre de Cristo Formation. Also, they bring out the curious fact that only a small part of the Cenozoic Era, some 70 million years long, is represented by any rocks at Philmont; and, because most of the Cenozoic rocks of Philmont lack fossils, we end by knowing less about the Cenozoic than about some earlier eras.

Once the geologic ages of the metamorphic and sedimentary rocks are known, we can work out, at least roughly, the geologic ages of the igneous rocks. The pink granodiorite and diorite porphyry, which are confined to the areas of Precambrian metamorphic rocks and are themselves slightly metamorphosed, are older than the Sangre de Cristo Formation and



BRINGING TOGETHER TWO KINDS OF TIME: geologic and clock. If the rhyolite lava has a radioactivity age of 400 million years and the granite, 350 million years, the Devonian formation is between 350 million and 400 million years old. (Fig. 91) therefore are of pre-Pennsylvanian age; most likely, they are Precambrian and only a little younger than the gneiss, schist, and quartzite. The dacite porphyry and andesite are of Tertiary age—younger than the early Tertiary Poison Canyon Formation but older than the oldest Quaternary gravel. The andesite is the younger of the two, for andesite sheets cut across dacite sheets north of Baldy Mountain. The lamprophyre and dark diorite, which are definitely younger than the Pierre Shale and older than the gravel, are probably of Tertiary age, too. Their age relations to each other and to the dacite and andesite are unknown. The lava flows and bomb beds associated with them are of Cenozoic age, as they are younger than the Late Cretaceous Pierre Shale and the presumed Tertiary dacite porphyry sheets that cut the Pierre, but are older than the late Cenozoic landslides. Probably the basalt is Tertiary rather than Quaternary but of much later Tertiary age than most, if not all, the other igneous rocks.

To show the rocks more vividly than on the flat geologic map, the surface geology has been sketched from the same bird's-eye position as the landscape model of plate 1. This geologic model (pl. 4, in pocket) is too small to show individual formations; instead, all the formations belonging to the same period or era are grouped together, and many small rock bodies, just large enough for the geologic map (pl. 3), are left off. Comparing the landscape model and the geologic model, we see that the patterns made by the rocks are like the pattern of the landscape units, and we begin to realize that the landscape did not just happen but is in some way controlled by the rocks beneath.

MISSING LAYERS

The Philmont cake has many missing layers, as plate 2 shows; indeed, rocks of more geologic periods are absent than are present. Rocks missing are just as important to the geologic story as rocks present: they tell of ancient landscapes and of times when old rocks were being eroded rather than new rocks deposited; they help to locate the source areas of old sediments and to trace the paths of former rivers and the wandering shorelines of vanished lakes and seas. Old surfaces of erosion, preserved by a cover of younger deposits, are called unconformities.

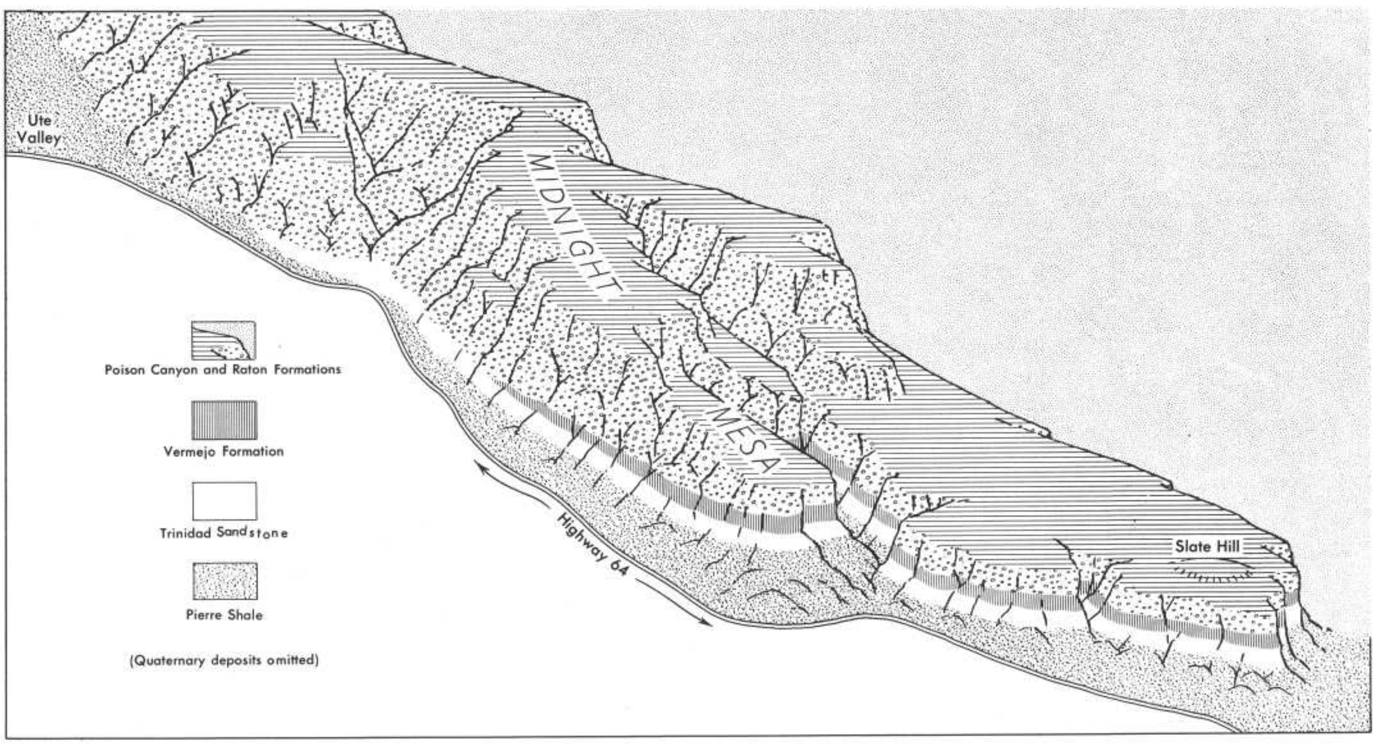
Starting from the top of the Philmont rock pile, we promptly meet a swarm of unconformities, represented by flat dissected deposits of stream gravel and sand at several levels in the lowland plains. Valleys had to be cut through each higher gravelled surface before the streams could establish themselves and deposit the next lower gravel; each episode of valley cutting resulted in an unconformity. In parts of the lowland plains, as many as four successively narrower and lower valley steps can be seen (three are visible in figs. 2, 8). No fossils have been found to date the times of gravel making; but probably no one of these unconformities represents very much geologic time, for all the gravel, even the oldest and highest, is loose and not much weathered.

The gravels as a whole, though, bespeak a large unconformity. They all seem to be of Quaternary age and no more than a million years old. The youngest rock preserved beneath them at Philmont—the Poison Canyon Formation—is very early Tertiary, probably more than 60 million years old. This would suggest that all Philmont was being slowly eroded during the tens of millions of missing years.

Another possibility becomes evident when we learn that Tertiary rocks younger than the Poison Canyon are still preserved nearby. Beginning abruptly a few miles north of Philmont and continuing for more than 50 miles along the mountain front are sands and gravels thousands of feet thick that were deposited by mountain streams in early and middle Tertiary time. Philmont was very likely blanketed by some of these same soft rocks, but they were stripped off in late Tertiary time.

The same unconformity that underlies the gravel goes under the basalt cap of southern Philmont.

Beneath the Poison Canyon and Raton Formations is another, rather small, unconformity (fig. 92). It is easily seen from Highway 64 and on the geologic map.

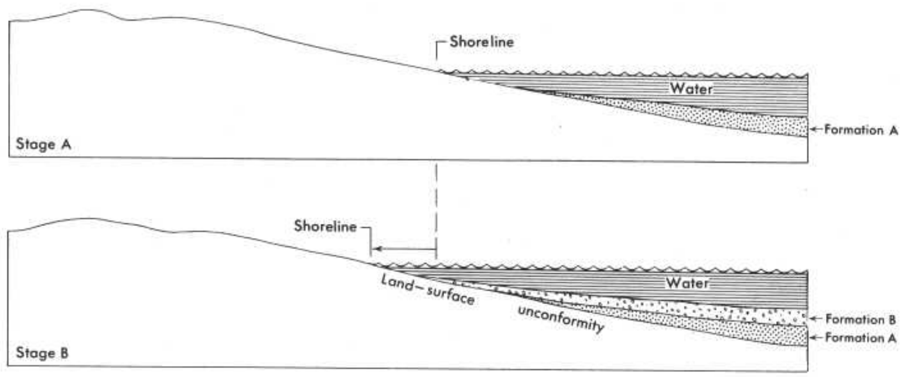


UNCONFORMITY beneath Poison Canyon and Raton Formations along U.S Highway 64. (Fig. 92)

Downstream from Slate Hill near Cimarron, the Raton Formation lies on 150 feet of the Vermejo Formation. At the base of Midnight Mesa, the fine-grained Raton intertongues with, and is displaced by, the coarse-grained Poison Canyon Formation, still lying on the Vermejo, which here, however, is considerably less than 100 feet thick. Near the entrance to Ute Creek Valley, the Vermejo thins to nothing, and the Poison Canyon lies on the 100-foot-thick Trinidad Sandstone. Within a mile to the northwest, the Trinidad too disappears, and the Poison Canyon lies on the Pierre Shale. The unconformity, therefore, cuts down across more than 200 feet of beds within a few miles. As the rocks above the unconformity are only slightly younger than the rocks below it, the break does not signify much time.

Thinning does not by itself prove unconformity. Every sediment, of course, thins to nothing at the edges of the valley, lake, or sea in which it is deposited; and as the boundaries of the sediment traps change—for example, as the sea advances across a continent—new formations may lap over the edges of the old ones and onto still older ones (fig. 93) without much change in conditions or break in the record. The Poison Canyon Formation, however, was not deposited by a sea moving west but by streams flowing east. Conditions changed radically between Trinidad time and Poison Canyon time, and the Poison Canyon Formation does not overlap the Trinidad but lies unconformably on it.

All the periods from the Cretaceous down through the Pennsylvanian are represented by rocks at Philmont. If there were episodes of erosion in this long span, or times when the region stood close to sea level and far from sources of sediment so that there was neither erosion or deposition, they were not long.



THINNING of a formation by overlap. (Fig. 93)

Below the Pennsylvanian part of the Sangre de Cristo Formation is the greatest unconformity recorded at Philmont. There are no Mississippian, Devonian, Silurian, Ordovician, or Cambrian rocks, representing nearly 300 million years, nor any Precambrian rocks to fill the rest of the gap from the start of the Cambrian, 600 million years ago, to the gneiss and schist, 1,000 million or more years old. The rocks that became gneiss and schist must have been squeezed, recrystallized at depth, and deeply eroded before the Sangre de Cristo beds were laid down. Evidence from surrounding areas does not help greatly in deciding whether any rocks were deposited here during this vast stretch of time. On the one hand, no rocks representing this time interval are known at the surface or in wells drilled for oil for scores of miles in any direction. On the other hand, the composition and thickness of the nearest pre-Pennsylvanian Paleozoic formations suggest sea rather than land at Philmont; rocks may have been deposited here during some or all of the first five Paleozoic periods, only to be eroded before Sangre de Cristo time.

Another great unconformity may be concealed in the metamorphic rocks. Possibly, the rocks that are now coarse-grained gneiss and schist were formed and partly metamorphosed before the rocks which became fine-grained schist and quartzite were even deposited, and then all these rocks were metamorphosed together. This might explain the great difference in grain size.

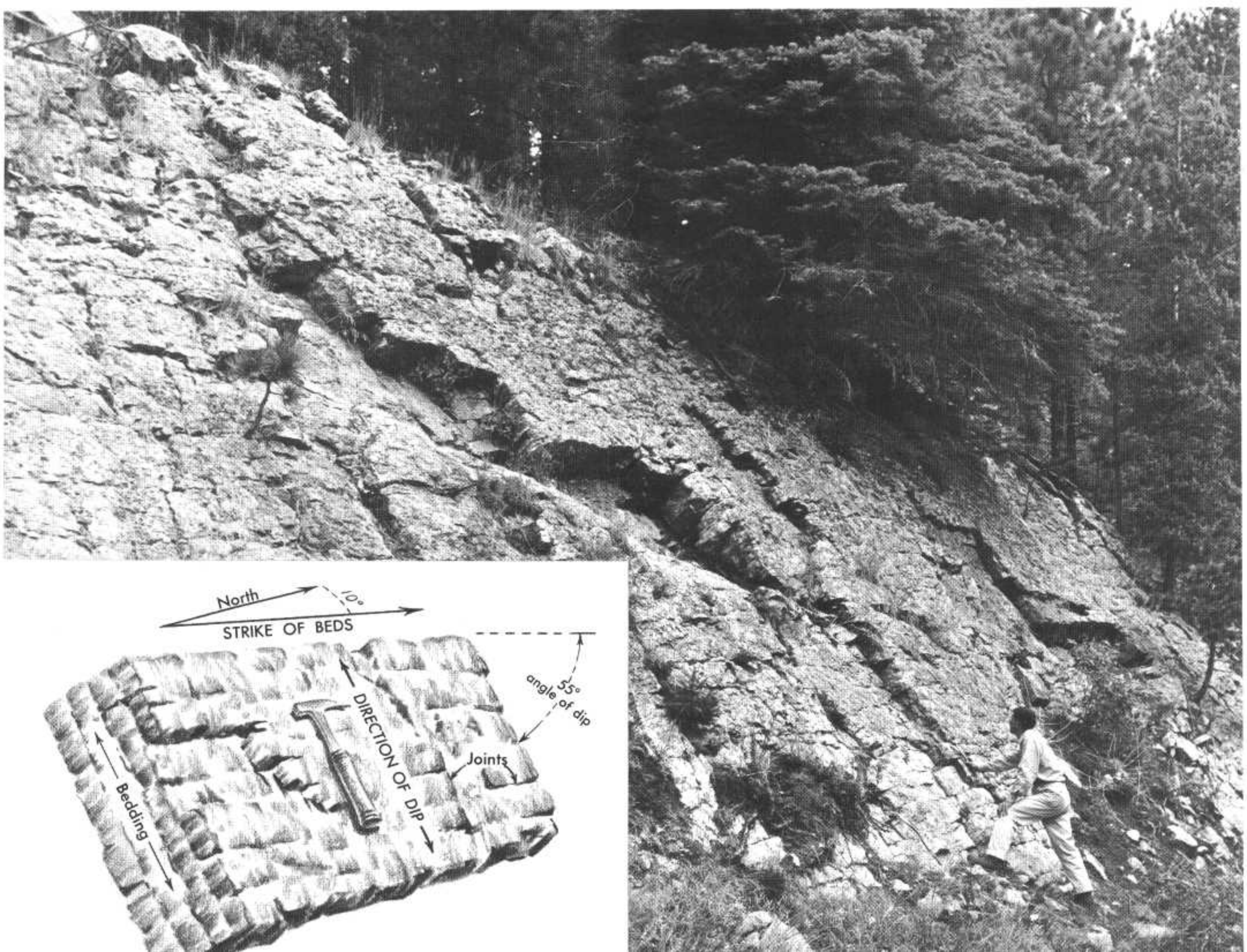
SUBSURFACE GEOLOGIC PROCESSES AT WORK

By observing the rocks and their relations to each other, we have begun to see Philmont as a sort of gigantic layer cake. Badly made to begin with, our cake has endured unceasing troubles. It has, of course, been constantly attacked from without by weather and running water whenever it has been above the sea; more about this in the next chapter. Now we will consider troubles from within.

Many of the sedimentary layers at Philmont do not simply hug the surface, like the skin of an onion, but dip into the earth, in places very steeply; the exposed edges of such layers suddenly end in the air. But the rocks were not formed this way. Most sediments collect on the ocean floor or on river flood plains in almost flat-lying beds that taper gradually to their edges, so that each bed has the general shape of a pod or lens, whether it is small enough to hold in the hand or large enough to blanket half the United States. A few coarse-grained deposits have been seen to form at initial dips of several degrees, but such dips are out of the question for fine-grained soft sediments in water: until they harden they cannot maintain an upper surface that has much slope; rather, they flatten out by flowing and sliding. Therefore, beds of fine-grained waterlaid rocks having dips of as much as 1° (about 100 feet to the mile) or more must have been tilted or bent after the rock was solid.

A layer that is tilted or bent and then eroded appears as a strip or belt cutting across country. The trend of the edge of an eroded layer is called the strike, and its slope is the dip (fig. 94). Together, the strike and dip of a surface are called its attitude.

DIP AND STRIKE of a sandstone ledge. This outcrop, of Dakota Sandstone, is on the lowest switchback in the trail west of Crater Lake Base Camp. (Fig. 94)

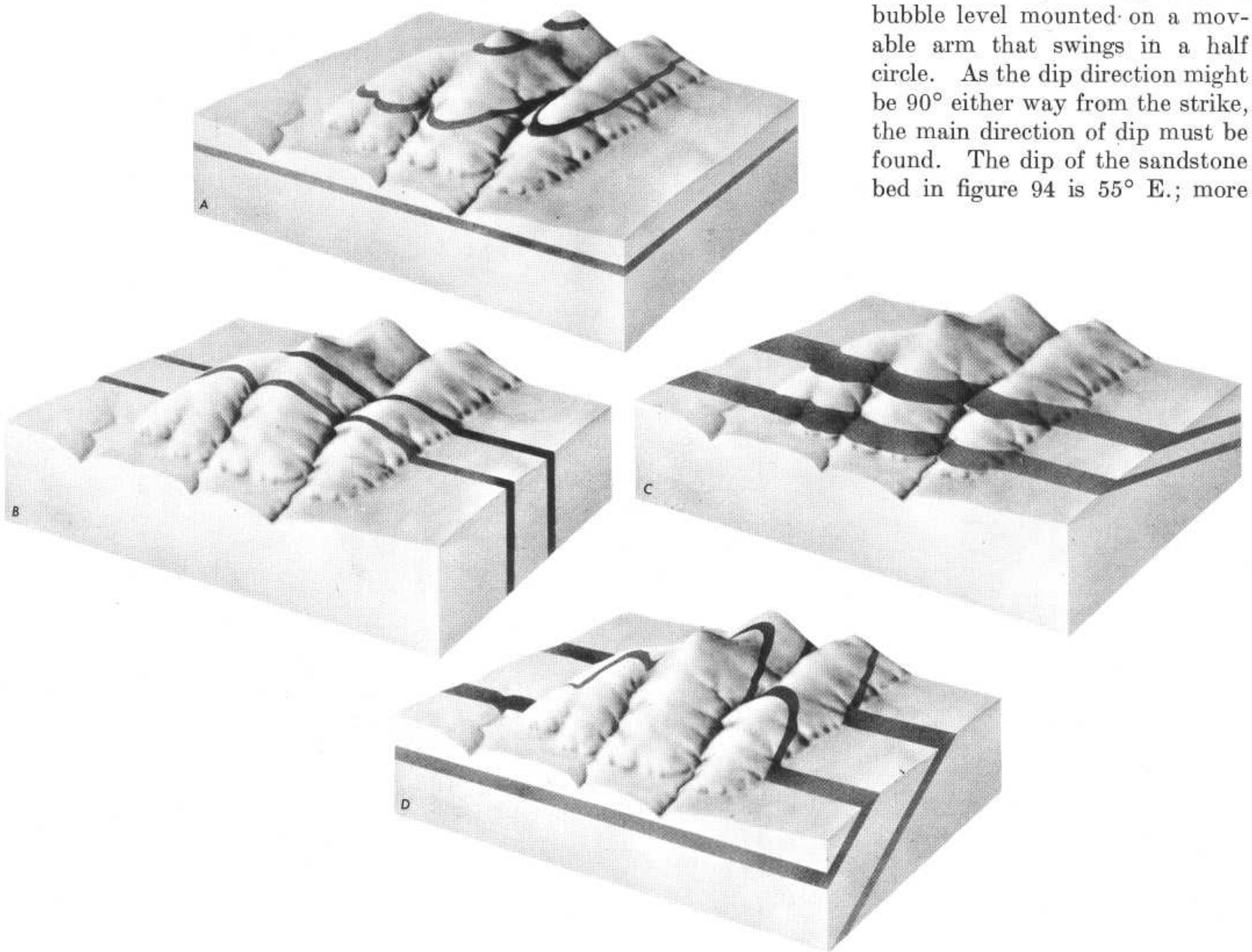


More precisely, the strike is the direction of the intersection between a dipping surface and a horizontal plane. The surface of a lake is a horizontal plane, and a good way to visualize strike is to imagine that the tilted bed forms the shore of a lake and dips beneath the lake, as in figures 97 and 98.

Measuring the tilt of beds

Measurements of strike and dip are the main tools used to learn about the kind and magnitude of rock deformation, or rock structure, in the earth's outermost skin. A good idea of the attitude of rock layers can be had by noting the shapes of outcrop belts in dissected country (fig. 95). More accurate measurements can be made with a compass and are usually expressed in degrees from true north. (Compasses in the northern hemisphere point to magnetic north, not true north, and allowance must be made for this magnetic deviation. At Philmont, the compass points 13° east of north.) The strike of the sandstone bed in figure 94 is north 10 degrees east, abbreviated N. 10° E.; the strike is also, of course, south 10 degrees west (S. 10° W.), but it is unnecessary to record this. The strike of east-west beds is N. 90° E. or N. 90° W.

Dip is measured at right angles to the strike, in degrees from zero (flat) to 90 (vertical), with a bubble level mounted on a movable arm that swings in a half circle. As the dip direction might be 90° either way from the strike, the main direction of dip must be found. The dip of the sandstone bed in figure 94 is 55° E.; more

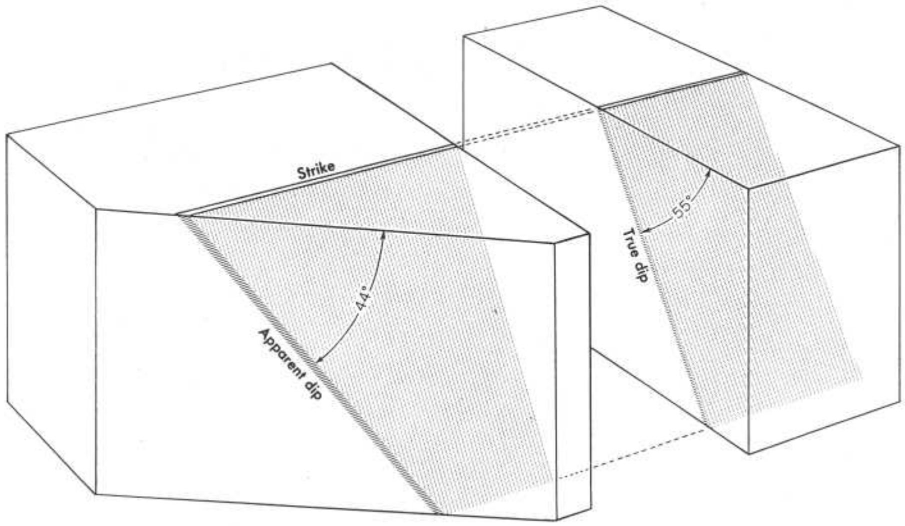


TOPOGRAPHY AND DIP affect the outcrop pattern of layered rocks. A, Beds that lie flat or nearly so crop out in patterns that outline the land forms. In rough country, like most of Philmont, their outcrop patterns are intricately scalloped and patchy. B, Layers that stand vertically or nearly so run straight across the landscape, whether it is rugged or subdued. C and D, Layers that have moderate to steep dips make curved patterns somewhere between the scalloped and the straight. If the dip is opposite to the direction of streamflow, the outcrops of layers crossing valleys make V's pointing upstream (C). If the dip is in the direction of stream flow, the V's point downstream (D). (Fig. 95) precisely, it is 55° in a direction 80° east of south, or S. 80° E., but this need not be stated, because dip is measured at right angles to strike, and this direction can be found simply by adding or subtracting 90° from the strike direction. It is enough, then, to state whether the dip is eastward or westward. Similarly, if a strike is nearer to east-west than to north-south, say N. 50° W., the dip is given simply as degrees north or south, for it must be either in a direction 90° north or 90° south of N. 50° W., that is, N. 40° E. or S. 40° W.

As shown in figure 96, the true dip can only be found by measuring at right angles to the strike: at less than a right angle, the apparent dip is progressively lower than the maximum or true dip until the dip seems to be zero parallel to the strike. This is why the rocks north of Cimarron look flat from Highway 64, though they actually dip northward: the road is nearly parallel to the strike.

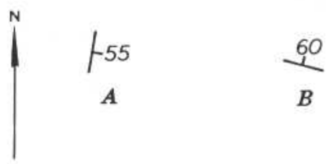
A compass needle for measuring strike and a movable level for measuring dip are combined in the geologist's, or Brunton, compass. Figures 97 and 98 show this instrument and how it is used. It is better to stand away from the outcrop and take average measurements rather than to place the instrument against the outcrop. Dip and strike in disturbed rocks vary a lot in short distances, and "accurate" measurements on a very small part of an undulating surface would be meaningless.

It is also wise to measure dip on beds well within a formation. Measurements on the upper surface of a formation may be misleading, for the upper surface may slope more or less steeply than the bedding, as a result of later erosion; and the base may also slope, owing partly or wholly to deposition on an irregular or sloping surface, rather than to deformation.



TRUE AND APPARENT DIP. The true dip is at right angles to the strike. Seen at any other angle, the dip appears lower. This makes it easy to underestimate dip. (Fig. 96)

Strike and dip are usually shown on a geologic map by a short-bar T. The top of the letter is the strike. The map symbol for the example we have been using—strike N. 10° E., dip 55° E.—is shown as *A* below, and another example—strike N. 75° W., dip 60° N.—is shown as *B*.



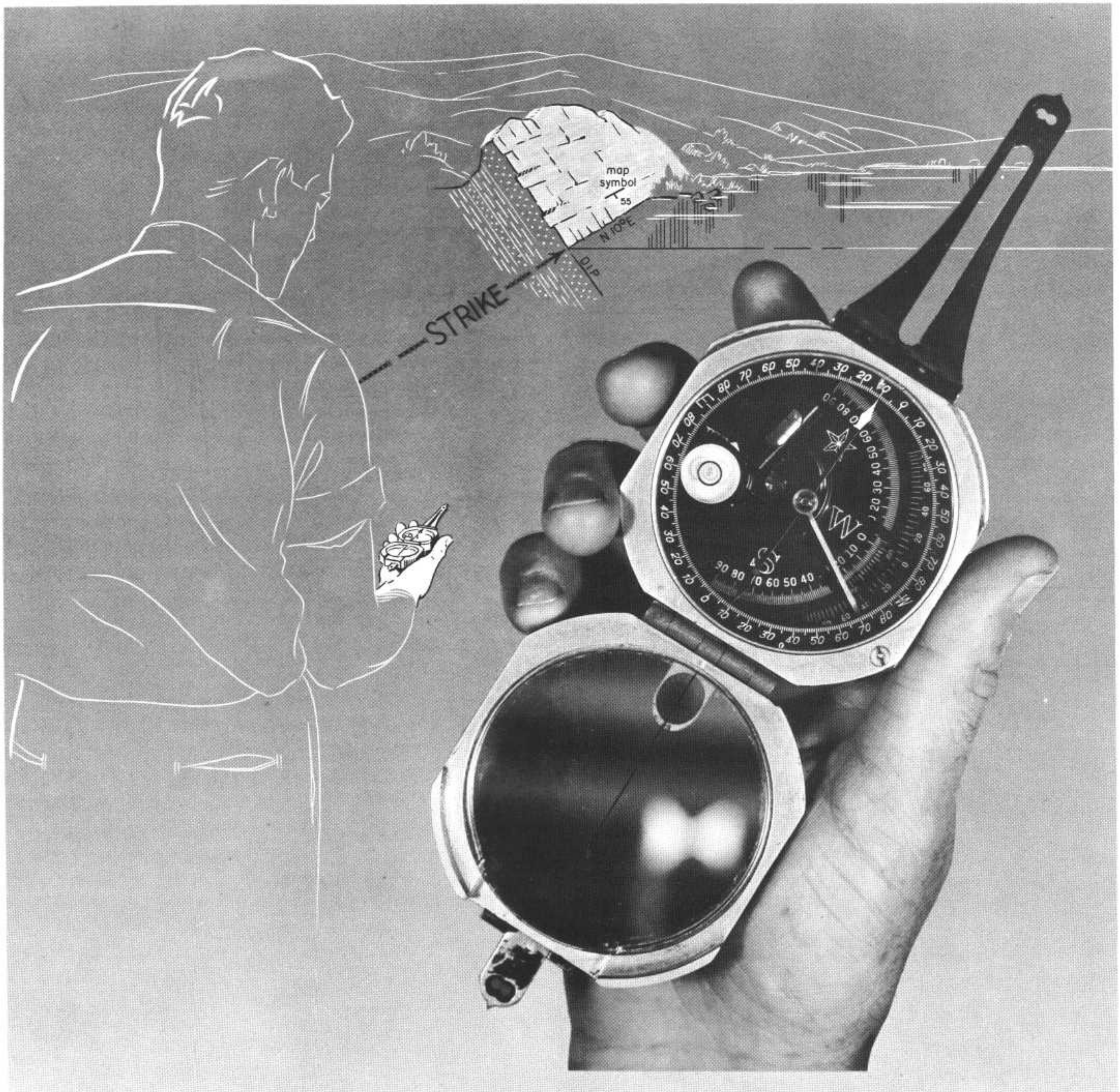
When later we speak of low or gentle dips, we mean dips of less than 10°; moderate dips are those between 10° and 40°; and steep dips are greater than 40°.

Only a few dips and strikes are shown on the geologic map (pl. 3). These were recorded to the nearest 5° except that dips of 1° to 3° are given as 2°. Although dip and strike are usually measured directly in the field, they can be measured on a carefully made geologic map that has an accurate topographic base (but not on quickly made plate 3!), or even on stereoscopic pairs of aerial photographs.

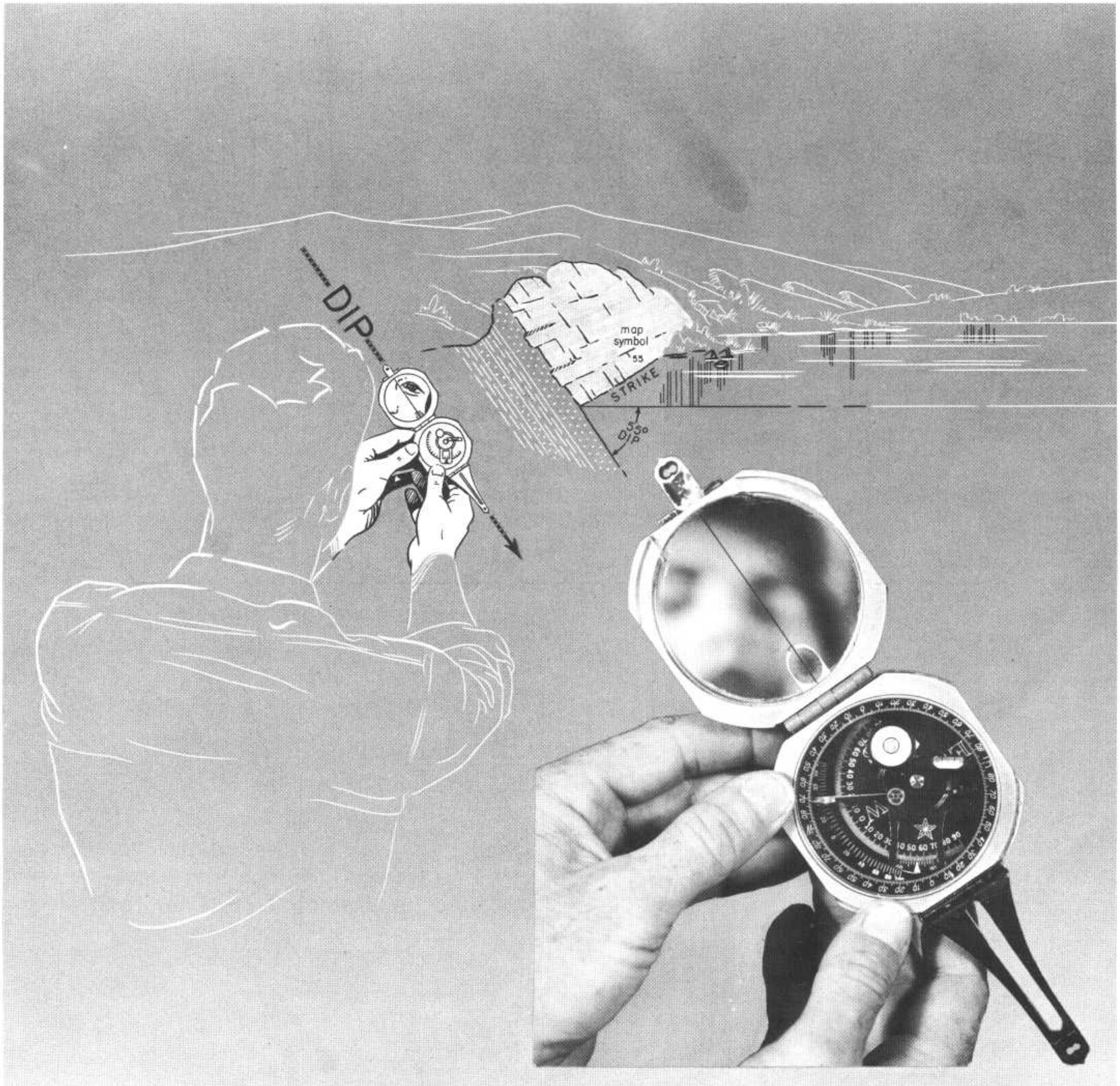
With the help of dip-and-strike information, we can learn something of the earth movements that have interrupted the piling up of layers at Philmont. Knowing the geologic ages of the rocks, we can also decide when these movements happened.

Deformed layers: Tilted and folded rocks

If layered rocks are deposited on the earth's surface nearly flat, we realize that all the named formations at Philmont must have been disturbed, or deformed, to some extent after they became solid, for most of them have marked dip. A reasonable prediction would seem to be that the older the rocks, the greater the deformation. Using the steepening of dip as a fair guide to the degree of deformation and taking the scattered attitude symbols on the map as representative, we can quickly visualize where and



USING THE GEOLOGIST'S COMPASS TO MEASURE STRIKE. First the compass is set for the average magnetic declination by turning a set-screw on the side; at Philmont, 13° E. Then it is leveled by centering the bubble in the bull's-eye and is lined up parallel to the strike. The strike, read directly from the dial marked in degrees, is N. 10° E. in this example. Note that the symbols for east and west are reversed: to take a reading, the body of the compass is turned while the magnetized needle stands still, so that rotating the compass to the east, as in this example, makes the needle seem to move west. Any compass can be used to measure strike. This kind is simply more accurate than most and gives a direct reading. (Fig. 97)



USING THE GEOLOGIST'S COMPASS TO MEASURE DIP. The compass, turned on edge, is lined up parallel to the dip. Then, by means of a lever on the back, a movable arm that has an attached bar level is rotated until its bubble is centered. The angle between the centerline of the compass and the axis of the bar level is the dip—in this example, 55°—which is read directly from the innermost scale, marked in degrees. A simple dip measurer can be made with a protractor, a string and a small weight. One end of the string is attached to a hole at the center point, the other end to the weight which is allowed to hang free. The protractor is rotated until it is parallel to the dip, and the angle of dip can be read directly. (Fig. 98) how much the sedimentary rocks are deformed. By doing so, we find that the "reasonable prediction" is a bad guess. The solid rocks of the northern benchlands are the least deformed, having dips generally under 10°; those of the mountain front are the most deformed, having dips typically 25° to 45° and many much steeper; and those of the plains and along upper Cimarron Canyon are somewhere between. This is not at all the order of relative age of the rocks in those areas. Furthermore, some of the same formations that crop out both in the plains and in the mountains have widely varying dips. It is even true that certain younger formations in some places have much steeper dips than older ones elsewhere; for example, the Dakota Sandstone (Cretaceous) on upper South Fork Urraca Creek is turned up to vertical, whereas the much older (Permian and Pennsylvanian) Sangre de Cristo Formation on Cimarroncito Creek has moderate dips.

Yet it is hard to deny that, where movements are going on, only rocks that have not yet formed can escape being deformed. Some kinds of deformation must, therefore, be confined to narrow belts of country and not be felt elsewhere, so that the degree of deformation in rocks is not a sure guide to relative age. Anyone who likes puzzles will see at once that the study of rock disturbances or deformations—structural geology—can be fascinating.

The Philmont area has its share of structural puzzles. Before we get to them, let's look at some of its least puzzling structures, starting with the simplest.

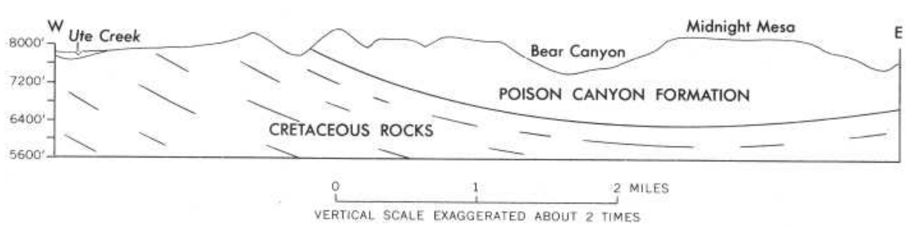
If the dip of a slab of sedimentary rock is uniform and all in one direction, the slab has probably been tilted. The gravel caps of the lowland benches seem to have been tilted slightly down to the east. The base of the cap that extends almost unbroken for 4 miles from Webster Reservoir near Cimarroncito Creek to Highway 21 drops 400 feet in that distance, or 100 feet per mile. The cap that extends many miles eastward from the conspicuous white buildings of Nairn Place, near Urraca Creek 1.2 miles east of the Stockade, has about the same slope, or a little steeper, and so does the cap along the north side of lower Rayado Creek.

Of a still higher graveled bench level, only scraps are preserved at such places as the east end of Horse Ridge and on Kit Carson Mesa, south of Carson Maxwell Base Camp; this slope is hard to measure, but it seems to be well over 100 feet per mile. If these gravels were deposited by streams flowing east, some or all of this dip might be original. But there are reasons (coming later) to think that these gravels were dropped by the ancestral Canadian River, flowing south; if they were, the eastward dip is due to tilting.

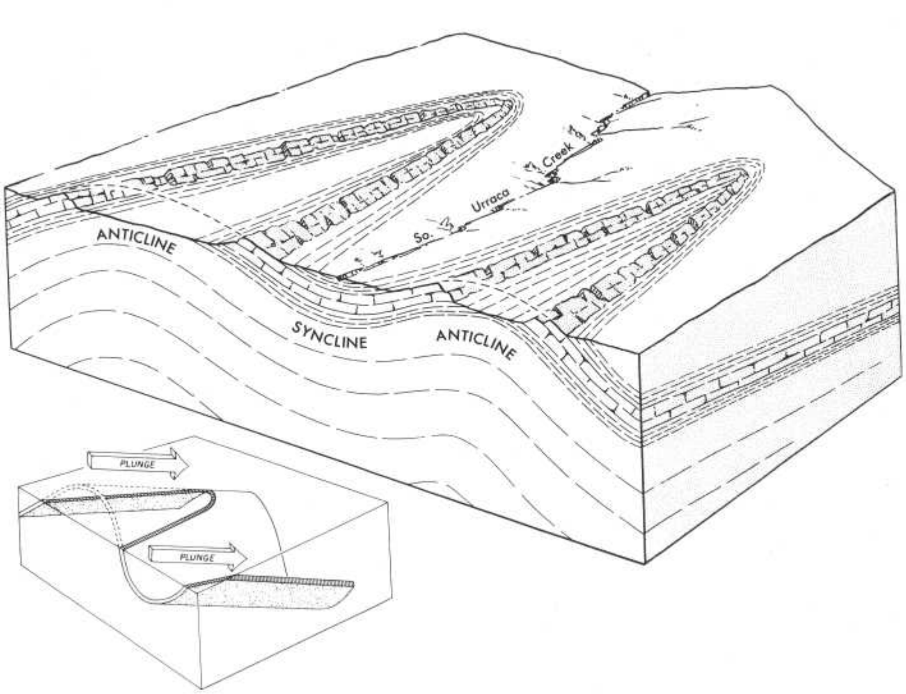
The basalt of the southern benchlands has been tilted, too. The dissected lava cap north of Rayado Creek slopes northeast at about 200 feet per mile, or more than 2°, and so does the base of the lava pile of the Ocaté Mesa. As basalt was not a waterlaid sediment but was a very thick liquid when it was laid down, we cannot assume that it started flat; at least some of its dip was the dip of the surface on which it flowed. At any rate, the basalt, being older than the gravel caps but near them, has surely been tilted eastward as much as the gravel.

At first sight, simple tilting seems also to explain the steady northeasterly strike and low northwesterly dips—all near 2°—in rocks of the Raton and Poison Canyon Formations along Ponil Creek between Highway 64 and Ponil Base Camp. But to the west the strike and dip of these rocks change, so that along Ute Creek valley they strike west of north and dip 5°–10° NE. These changes show that the Raton and Poison Canyon Formations north of Cimarron Creek are not merely tilted but are folded into a broad shallow scoop shape (fig. 99). Such a downfold, in which the rocks dip inward, is called a syncline, from the Greek for "dip toward." This syncline is so broad and has such low dips that it is hard to recognize on the ground; but synclines come in all sizes, and there are others at Philmont that are easier to figure out, as they are smaller but have steeper dips.

A syncline that is fairly easy to reach and to recognize is crossed by South Fork Urraca Creek west of the trail turnoff to Stone Wall Pass. There, as figure 100 illustrates, the Fort Hays Limestone Member on the north side of the



GIANT SHALLOW DOWNFOLD, or syncline, in Poison Canyon rocks north of Cimarron Creek. Dips exaggerated. (Fig. 99)



FOLDS IN SEDIMENTARY ROCKS on lower South Fork Urraca Creek. Stream and landslide deposits omitted. (Fig. 100)

creek dips moderately south, and the Carlile Shale, cropping out on the hillside to the north, and dips beneath the limestone. These south-dipping rocks are also shown in figure 30*A*. The shale in the creek bed to the south lies on top of the limestone and is, therefore, the upper part of the Niobrara Formation. A little farther upstream, outcrops of the limestone on the south side of the creek dip toward the trail, or northeastward. The limestone, then, dips toward the creek from both sides: it has been folded into a trough shape.

Other, somewhat broader but shallower synclines have been mapped in the Cretaceous rocks of the plains to the south. Probably, too, the rocks beneath Deer Lake Mesa are folded into two shallow bowl-shaped synclines, each marked by a surface basin—Devils Wash Basin and Deer Lake—but we did not make enough dip and strike measurements to prove this.

If rocks can be folded down into trough, scoop, canoe, or bowl shapes, we would suspect that they can also be folded up into matching shapes, for folding a pile of layered rocks ought to be much like folding a pile of paper. (Remember that a pile of paper can be folded in several ways: pushing from one side or from several sides is perhaps the most obvious, but putting weight on part of the pile or pushing up on part of it will also serve.) It is no surprise, then, that a little west of the syncline where the Urraca trail turns sharply southwest, the dip of the limestone is again reversed so that it is southwest. These opposing dips outline an archlike upfold called an anticline, from the Greek for "dip away." The sides or limbs of this pair of folds are not parallel but make a zigzag pattern, as shown in figure 100. This outcrop pattern means that the trough of the syncline and the crest of the anticline are plunging toward the plains. If the crests and the troughs of the folds were flat, the beds would crop out in parallel stripes.

Some broader and shallower anticlines than the one we have just noticed can be recognized in the Cretaceous formations to the south.

If Devils Wash Basin and Deer Lake are truly in the troughs of separate small synclines, then there must be a low anticlinal arch between. Also, at least one anticline must be concealed by the landslide between Deer Lake Mesa and Midnight Mesa, for the dips seem to be in opposite directions on the mesa flanks that face each other.

The ledge of Fort Hays Limestone Member on the north limb of the syncline sketched in figure 100 is on the south limb of a much larger domelike anticlinal structure. This limestone ledge makes a nearly unbroken loop that is 2½ miles long, extending from near the Shaefers Pass Trail to just east of the Stockade, and 1½ miles wide, from Urraca Trail to the middle of Tooth of Time Ridge; the limestone dips outward from the center of the loop, which is filled not by Carlile Shale, the next underlying sedimentary formation, but by dacite porphyry. Many of the mountain peaks flanking Highway 64 are near the crests of similar but much larger broad domes in which the sedimentary rocks are spread apart by sheets of dacite porphyry. More will be said about this kind of anticline when the structures of the igneous rocks are discussed.

From the traverses up Rayado Creek and across the Cimarron Range, we saw that the whole range is a huge anticlinal arch, being broader even than the syncline north of Cimarron Creek and having much steeper dips on the flanks. The small folds east of the mountain front may be thought

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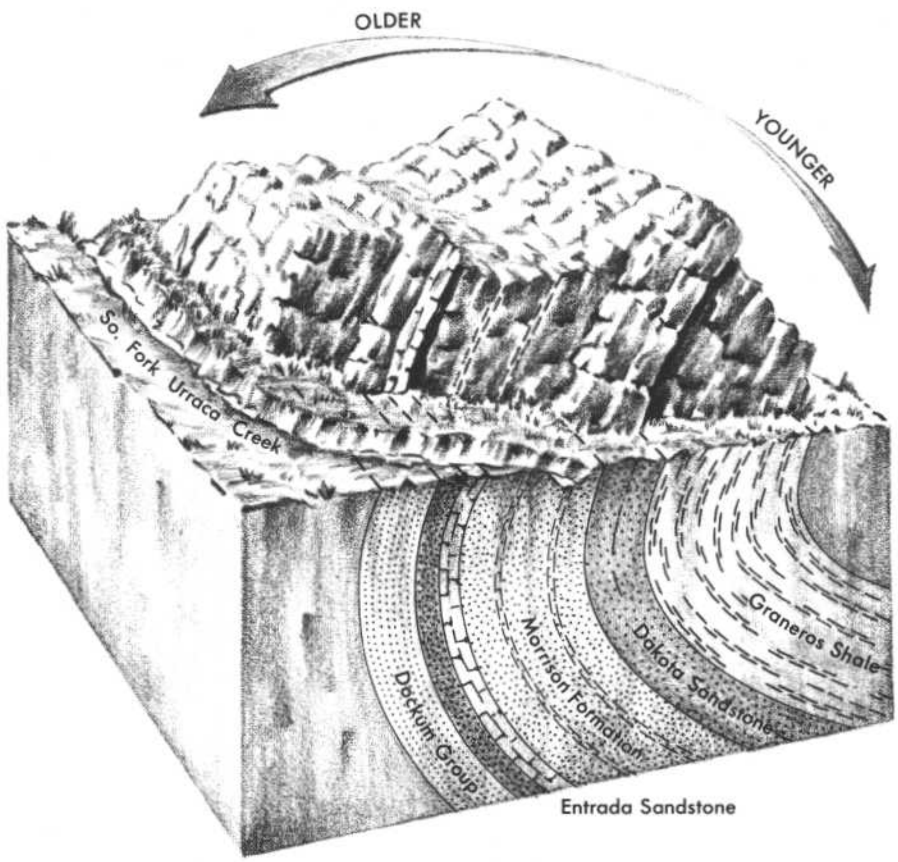
of as wrinkles on this superfold, or ripples on the side of a giant frozen wave.

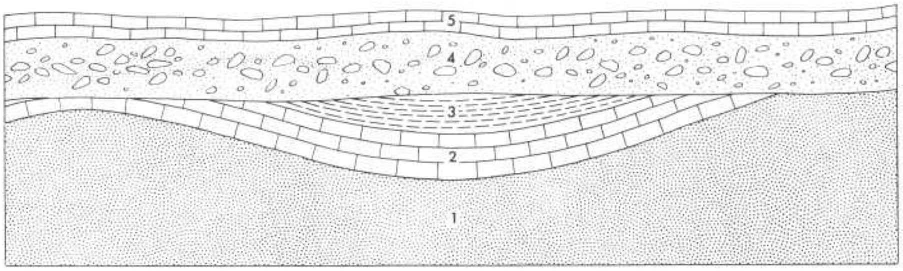
In a few places these wrinkles have been so tightly folded that the rocks are overturned. For instance, at the mountain front on the South Fork Trail, the sedimentary formations are bent so steeply that they are overturned, dipping 70° W. (fig. 101). We can tell that the Dockum Group in figure 101 is overturned, top to the east, and not simply in a fold, top to the west, because the beds that are below it to the east (fig. 102) are not the coarse-grained red rocks of the Sangre de Cristo Formation but are successively the white Entrada Sandstone, the red Morrison Formation, the ridge-making Dakota Sandstone, and the black Graneros Shale, all of which are known, from many observations where the rocks are less disturbed, to be above and younger than the Dockum Group. By climbing the hill north of the trail and walking along the strike, we can see the overturned beds change to vertical and then to their usual east dip, in normal sequence.

The geologic age of tilting and folding can be decided in a simple way. Any tilt or fold must be younger than the youngest rocks in it and older than the oldest rocks in the same area that are not tilted or folded (fig. 103). Between the deformed and undeformed rocks in figure 103 is, to recall the discussion of "missing layers," an unconformity, which represents a period of erosion that occurred after the tilting or folding and before the next rocks were deposited. When the unconformity is the result of deformation, so that there is an angle between the bedding above and below, it is an angular unconformity. The unconformity beneath the Poison Canyon and

SHALE AND SANDSTONE of the Dockum Group standing nearly vertical on South Fork Urraca Creek trail. (Fig. 101)



BEDS OVERTURNED at the mountain front on South Fork Uracca Creek. For a short distance on the north side of the creek, younger rocks dip under older rocks. (Fig. 102)



GEOLOGIC AGE OF FOLDING. In the drawing, formations 1, 2, and 3 are deformed but 4 and 5 are not. The rocks must have been disturbed and then eroded to a smooth surface after 3 was deposited but before 4. If 3 is Jurassic and 4 is Cretaceous, the folding happened late in Jurassic or early in Cretaceous time. (Fig. 103)

Raton Formations in northwestern Philmont described earlier is evidence of slight eastward tilting before Raton time but after Vermejo time and is therefore an angular unconformity.

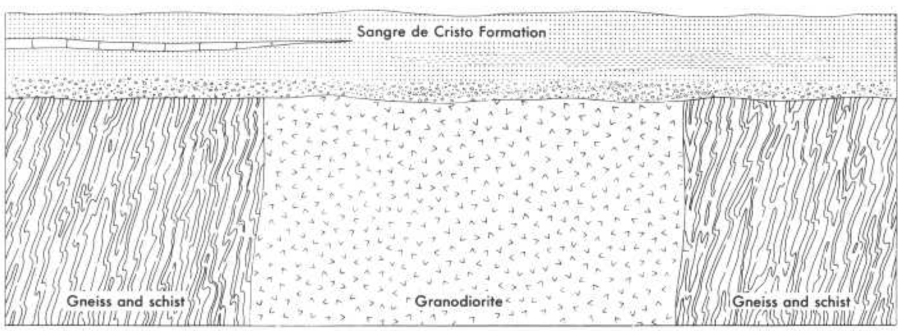
Using the simple guide of angular unconformity, we can decide that the broad syncline north of Cimarron Creek is younger than the Poison Canyon Formation but older than the landslides and all the loose sand and gravel on the plains and valley floors. The great Cimarron Range anticline is also younger than the Poison Canyon Formation. The main arching probably occurred in middle Tertiary time, but the tilting of the basalt flows and of the higher graveled benches shows that arching continued or recurred until fairly late Quaternary time; indeed, sensitive instruments might show that it is still going on.

The smaller anticlines and synclines south of Cimarroncito Creek are younger than the Pierre Shale and older than the unfolded basalt. These small folds, incidentally, are not easy to recognize because so much of them is covered by unfolded younger deposits. The folds must be reconstructed by piecing together scattered dips and strikes and, in imagination restoring parts planed off by erosion.

A reasonable guess is that the metamorphic rocks were tightly folded in Precambrian time before and during metamorphism; the layers in the metamorphic rocks are almost at right angles to the bedding in the Sangre de Cristo Formation, making the break between an extreme angular unconformity (fig. 104).

Anticlines do not necessarily mean bulges on the landscape, nor synclines depressions. Probably, folding is often so slow that erosion keeps up with it, and folds forming at depth may never appear as bulges or sags on the surface. The landform that grows on an eroding fold depends on the resistance of the different rocks to erosion. If the core of an anticline is made of rocks more resistant than those of the flanks, then it makes a high part of the landscape, like the Cimarron Range itself; but if the core rocks are less resistant, then the heart of an anticline may wind up at the bottom of the local scenery, like the valley of Urraca Creek between Shaefers Pass Trail and the Stockade. The same, in reverse, is true of synclines. Fold structures, then, are revealed in the dips of the rocks. They may or may not be shown by the landscape that forms on them.

Most of the world's mineral deposits are in folded rocks: metal ores are mainly in tightly folded rocks; fuels—coal, oil, gas, uranium—are mostly in gently folded ones. Modern mineral industries employ many thousands of geologists to find favorable-looking structures that might be explored for new deposits as well as to guide the development of known deposits. Mineral exploration demands special skill and imagination if the ore- or fuel-bearing structure does not crop out but is buried beneath an unconformity—or is the unconformity itself. To meet the increasingly heavy demands of industry, the ores and fuels, which are unreplaceable, are being dug and pumped out of the ground faster and faster. More and more new deposits must be found, and the search grows increasingly difficult and challenging. As time goes by, more and better geologists will be needed to find and to develop hidden mineral wealth.



ANGULAR UNCONFORMITY between Precambrian rocks and the Sangre de Cristo Formation. (Fig. 104)

Deformed layers: Broken rocks

Folding explains many of the large-scale deformities we see or interpret in the rocks at Philmont, but not all. Some of the rocks were deformed by breaking. An example is in the north wall of Cimarron Creek canyon, 7 miles west of Cimarron town, or 5 miles east of Ute Park. Exposed for 500 feet is an abrupt repetition of formations that cannot be explained by tilting or folding, as the photograph and sketches of figure 105 show. Upstream and downstream from this place, the Trinidad Sandstone makes a conspicuous cliff, the lower half nearly white and the upper half marked by two broad dark streaks separated by a narrow lighter colored band (these streaks are made by oil that seeped out of the rocks and dried in the air). Below the Trinidad Sandstone are scattered dark outcrops of Pierre Shale.

In this place, however, there is a sharp break in the cliff; and the entire Trinidad, streaks and all, reappears more than 100 feet lower, badly fractured but recognizable, and has Pierre Shale exposed below it in the cutbank of the creek. The sandstone and the shale are in their normal sequence and have the same low northward dip as the rocks uphill, so the repetition of beds cannot be the result of folding.

A reasonable conclusion is that the Trinidad and the Pierre have been repeated by movement along a break in the rocks that is about parallel to the main cliffs and is between the cliffs and the cutbank, as shown in figure 105*C*. The block of rock near the highway has moved relatively down, and the block farther away has moved relatively up. This is not merely a landslide; if it were, the block near the highway, especially the soft shale, would be all broken up, and the surface of movement would come out into the valley. The rocks still have their bedding, however, and the surface of movement dips into the earth. What happens to the break upstream and down is concealed by slide rock and vegetation, showing that the movement happened long ago.

We know little of the dip or shape of the break itself, so it is drawn straight and vertical in figure 105*C*. It might as easily dip moderately to steeply north or south or be curved and have changing dip. Only vertical movement is shown in the diagram, but there may have been either a little or a lot of undetected horizontal movement also. This interesting structure is too small to show on the geologic map.

Such abrupt displacements are called faults. This curious usage of a familiar word dates back several hundred years. It reflects the early British coal miners' uncomplimentary feeling about such structures. These men found faults to be a great nuisance, as many of the coal beds they dug were displaced by faults, and searching blindly for the offset part was wastefully expensive. Rocks the world over are broken by faults, and the structures are still a nuisance, not only in mining but also in the construction of dams, roads, and buildings. Faults also have their virtues: some are channels for ground water; others are traps for gas or oil; and still others are the sites of ore deposits. Fortunately, modern geologists can determine the amount and kind of movement on most faults, predict their effect, and, where necessary, direct the search for offset parts. This is another reason why thousands of geologists are employed by industries and public agencies that work with the earth.

Faults come in all sizes, from barely visible movements to tremendous breaks that can be traced for more than a thousand miles and along which rocks have shifted for several miles vertically and for hundreds of miles horizontally. No really immense faults seem to pass through Philmont, but a variety of small and middle-sized faults has been found here.

A fault larger than that along Cimarron Creek but not quite so obvious runs close to the trail from Miners Park to Shaefers Pass (fig. 106). The evidence of faulting on Cimarron Creek comes from repetition of beds. Faulting near the Shaefers Pass trail is shown by the absence of expected beds—the Carlile Shale and, for a short distance, the Fort Hays Limestone Member. Dips toward the fault from east and west suggest that the rocks were first folded. The missing beds indicate that the rocks were then broken, so that a block of rocks on the east dropped down, or a block of rocks on the west rose up, about 500 feet; on North Fork Urraca Creek, Carlile Shale is faulted against dacite porphyry. Later, erosion stripped the uplifted younger rocks off the west block. Big enough to name, we call this the Shaefers Pass fault.

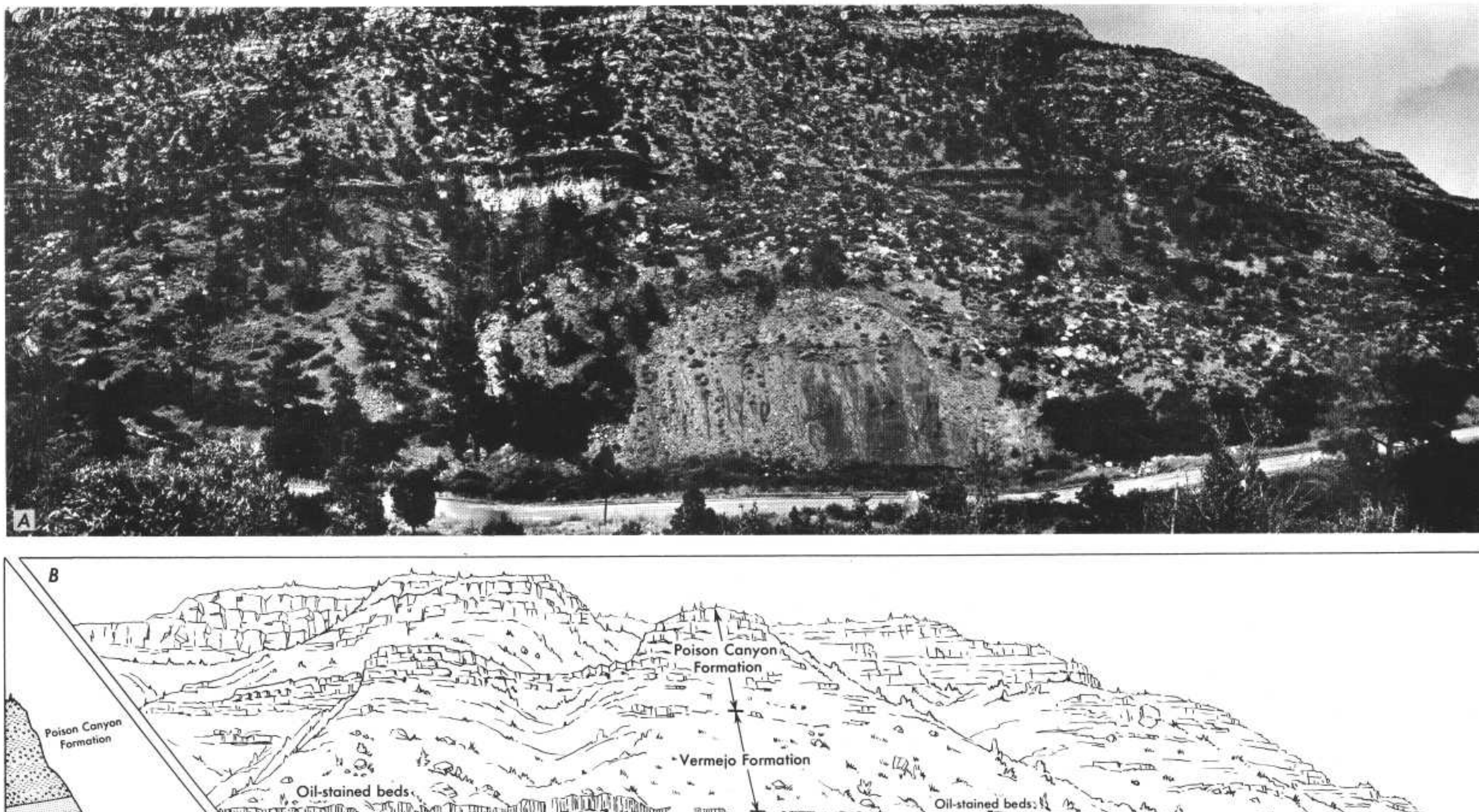
The fault itself is not exposed, and we can say little about its shape and dip; this is usually true of faults seen only on the surface. In figure 106A, the fault is drawn as vertical. If it dips eastward, as sketched in figure 106B, so that its sides, in effect, have pulled apart and the surface area has increased, it is called a normal fault. If the fault dips west, as in figure 106*C*, so that the sides are shoved together and the surface area has decreased, it is a reverse fault.

(Early geologists thought that most faults are the pull-apart kind and therefore called them normal faults. This is probably not so, but the names "normal" and "reverse" hang on.)

When did this fault happen? Had it moved hundreds of feet recently, the Quaternary slide rocks would be faulted too; and there would be a steep cliff, exposing shale and limestone, on the upthrown or western side. We conclude that the fault is not very recent, though it is, of course, younger than dacite porphyry, the youngest formation it cuts.

Signs of a much larger fault appear a mile west of the Shaefers Pass fault where the trail up South Fork Urraca Creek crosses the contact between Precambrian and sedimentary rocks (fig. 107). The Sangre de Cristo Formation, which is thousands of feet thick along Cimarroncito Creek to the north and along Rayado Creek to the south, is here reduced to but a few feet of broken rocks; the gneiss and schist at the contact are also broken and smeared out. Evidently, the contact is a fault.

Right on the contact is a zone a few feet thick of sticky dark clay containing scattered round boulders. The clay and boulders may

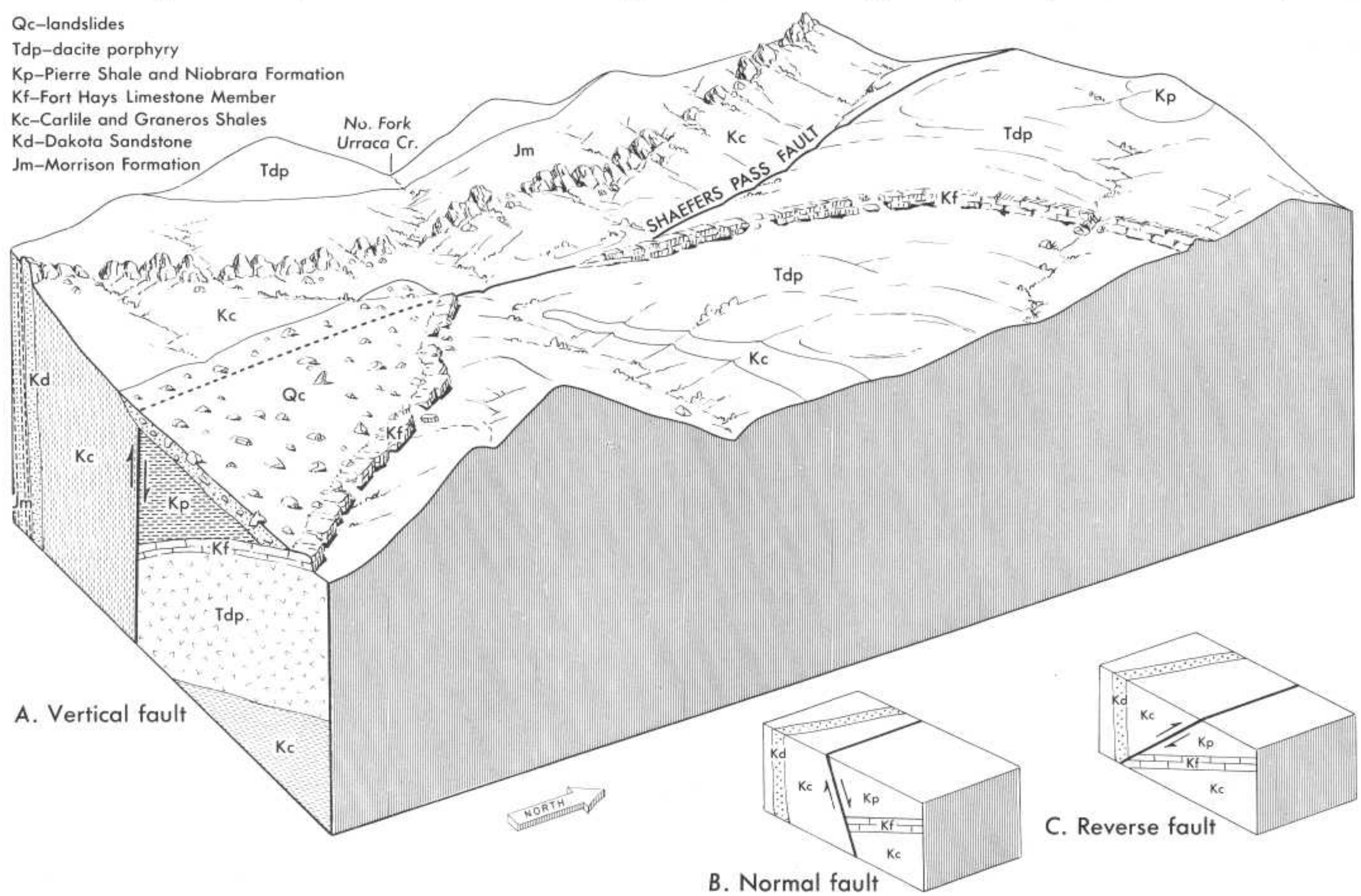


REPEATED BEDS along U.S. Highway 64. A, North wall of Cimarron Creek canyon. B, Sketch showing repeated beds. C, Slice through hillside, showing what happened. (Fig. 105) look like sediments, but they are not. The clay is soft wallrock that has been ground fine by repeated movement on the fault. The boulders are pieces of hard wallrock that have been caught up in the fault and rounded by abrasion but protected from further grinding by the clay. This outcrop does not reveal whether we are dealing with a normal, vertical, or reverse fault, but surely the mountain, or west, side has moved relatively up thousands of feet: the missing Sangre de Cristo rocks must have been eroded from the up side and must be below the surface on the down side.

To learn more about this fault, we must trace it beyond Urraca Creek. Doing so, we realize that it is a major feature, indeed. Southward, it continues without a break to Fowler Mesa. Covered by the lavas of Fowler Mesa and Rayado Peak, it reappears in Rayado Canyon and finally dives beneath the lava of Ocaté Mesa. It is responsible for the absence of Sangre de Cristo and Dockum rocks above Crater Lake Camp, and near Fowler Pass it cuts out the Entrada and Morrison Formations as well.

Near Fowler Pass are good exposures that give an idea of the dip of this fault. If the dip is vertical, the fault should go straight across hills and valleys alike, as do the vertical beds in figure 95*B*. If the fault dips east, it should bend downstream as it crosses the canyon north of Fowler Pass, as does a bed dipping downstream in figure 95*D*. Actually, the fault turns upstream (west), suggesting steep westerly dip, as does a bed dipping upstream in figure 95*C*. Crossing the canyon of Rayado Creek, the fault distinctly bends upstream, so we decide that it indeed dips westward. This means that older rocks have been shoved over younger ones, reducing the surface area. The fault is, therefore, a reverse fault. Its trend or strike is not the same as that of the formations bent up east of it, so that it cuts varying amounts of the formations which lie above the gneiss and schist. Because this structure is best seen near Fowler Pass, it is named the Fowler Pass fault.

The Fowler Pass fault has been traced for 16 miles across all of Philmont, as plate 3 shows; it probably continues for many miles



SHAEFERS PASS FAULT. A, Geologic diagram of area near trail to Shaefers Pass; fault shown as vertical. B, Drawn as though fault dips east; normal fault. C, Drawn as though fault dips west; reverse fault. (Fig. 106) beyond. For much of its length, the fault itself is obscured by dacite porphyry that has risen up along it.

The Fowler Pass fault was probably active in early Tertiary time. It is younger than the early Tertiary Poison Canyon Formation but older than the dacite porphyry and the basalt. If the Fowler Pass fault moved fast enough to make a cliff or scarp, the uplifted side was leveled by erosion before the basalt lava was poured out, as the base of the basalt is at the same altitude on both sides of the fault.

The west side of the mountain core of metamorphic rocks is also bounded by a steep fault. Like the Fowler Pass fault, this fault is so large that it is hard to see at any one place. We have named it the Lost Cabin fault, as it is well exposed only in the valley of Agua Fria Creek near Lost Cabin Trail Camp. It must be steep because it is so straight, but we do not know whether it is vertical or dips east or west. In the creek valley, rocks of the Sangre de Cristo Formation are dropped down on the southwest against gneiss and schist. As the thickness of beds cut out by the fault is not known, the amount of relative movement can only be guessed. It was surely hundreds of feet and may have been thousands. South of the valley, the fault is covered by unbroken basalt. To the northwest this fault forms the long sweeping smooth curve of the contact between basalt and metamorphic rocks, except where basalt crosses the fault in Wild Horse Park.

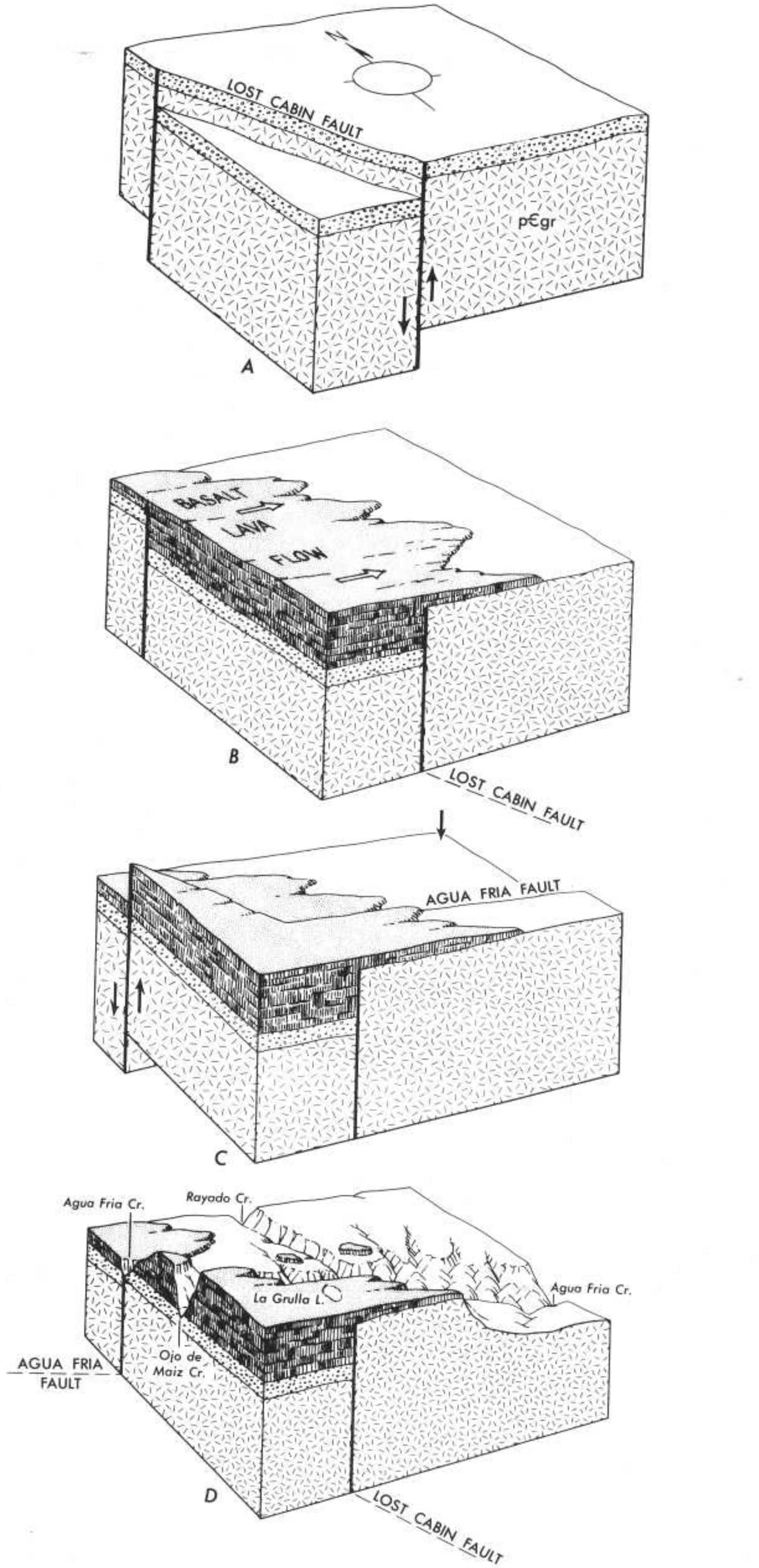
The Lost Cabin fault has some curious features that suggest a complicated history. Consider its relation to the basalt: is it younger or older? If the faulting is younger, the faultlike contact of basalt with metamorphic rocks on the north slope of Apache Peak makes sense, as does the general absence of basalt northeast of the fault: the basalt that once blanketed the upthrown (northeast) side was stripped by erosion, speeded up by uplift, which also wore away the original southwest-facing fault cliff or scarp. This sounds reasonable, but an equally reasonable story might go like this: Suppose that the fault were active long before lava was erupted and that the southwest-facing fault scarp acted as a dam to lava coming from a source to the south. The lava piled up against the scarp and flowed across the fault zone only where the cliff was low, as at Wild Horse Park. Continuing flow of lava near the source eventually buried the scarp on the south side of the creek. An added attraction of this reconstruction is that such a sequence fits the history of the Fowler Pass fault, and it becomes possible to think of the two faults as active at the same time, raising the core of metamorphic rocks and arching the overlying layered rocks.

But there was at least one more stage in the history of the Lost

ZONE OF GROUNDUP SHALY ROCKS AND ROLLED BOULDERS on Fowler Pass fault between Precambrian gneiss and schist (off picture to left) and Sangre de Cristo Formation on right. South Fork Urraca Creek. (Fig. 107)

Cabin fault, for still not explained is the low position of the peninsula of basalt east of the fault and on the north side of Agua Fria Creek. The base of this basalt body is more than 300 feet lower than the base of the basalt just across the creek to the southeast. Did the fault move again, but in reverse, so that the northeast side dropped down? If it did, why did not the basalt on the south side of the creek drop down too? We can perhaps solve this problem by noting that another fault runs east-northeast, roughly along the valley of Agua Fria Creek, for basalt on the hillside above Rayado Base Camp is also several hundred feet lower than basalt on the opposite canyon wall. Now we may imagine that a block bordered on the west by the Lost Cabin fault and on the south by the fault along Agua Fria Creek was dropped down a few hundred feet in the latest episode of faulting. The steps in this complicated reconstruction are shown in figure 108.

Having found one fault that seems to control lower Agua Fria Creek to its junction with Rayado Creek, we naturally ask if the valley of Rayado Creek downstream may not also be controlled by faults, for it has a zigzag path unlike those of other valleys to the north. No such faults can be seen between Rayado Base Camp and the foot of Rayado Peak, but their presence is strongly hinted by the fact that for miles the steep canyon walls are unbroken by any large side canyons although the walls of other large canyons at Philmont are deeply dissected. We reason that Agua Fria and Rayado Creeks may have cut their way rapidly downward in the crushed rocks along geologically recent faults, but that tributaries have not been able to do much cutting in the unbroken



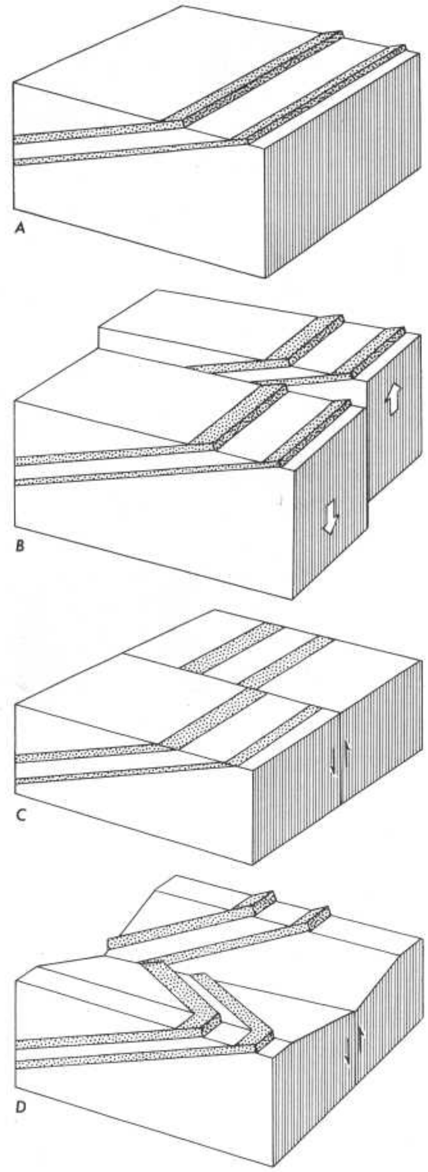
ONE WAY TO EXPLAIN THE GEOLOGIC STRUCTURE near the head of Agua Fria Creek. A, Birth of Lost Cabin fault. B, Erosion of sedimentary rocks from raised block, followed by lava flood. C, Birth of Agua Fria fault, south side up. D, Erosion of young fault zone to make Agua Fria valley. (Fig. 108) rocks on either side. If the zig-zag faults exist at all, there is no reason to think that they are nearly as large or as old as the Fowler Pass or Lost Cabin faults.

Whether or not faults control any part of upper Rayado Creek, the Creek definitely runs along a fault zone for at least a mile upstream from Old Abreu Lodge. The sedimentary formations from the upper part of the Sangre de Cristo Formation to the lower part of the Graneros Shale, all of which here strike north-northwest and dip about 30° E., are interrupted at the creek. Unlike the Fowler Pass and Shaefers Pass faults, which run along the strike of the formations, this fault, the Abreu fault, cuts squarely across the strike, so that the formations are offset about 300 feet, strata on the south side having moved relatively northeast. Perhaps this displacement was due to horizontal movement of 300 feet, but the same result could have been reached with even less vertical movement, as figure 109 shows. Owing to the moderate eastward dip of the beds, the same apparent horizontal shift would result if the south side had been raised only about 170 feet vertically. Vertical movement also fits the displacement observed upstream, where the block on the south side of the Agua Fria fault has been uplifted a few hundred feet in a late episode of faulting.

So far, we have described mainly vertical movements on faults, though admitting that horizontal movement may have happened too. At least one steep fault at Philmont could have resulted only from horizontal shifting. This fault offsets the vertical sheet of lamprophyre on Horse Ridge, on the north side of lower Cimarroncito Creek. About 200 feet from its west end, the sheet is abruptly offset 7 feet, as figure 110 shows. As this is about the thickness of the lamprophyre, the north edge of the western part of the broken sheet now lines up with the south edge of the eastern part. This fault is far too small to show on the main geologic map, so a special enlarged map of it has been drawn (fig. 111).

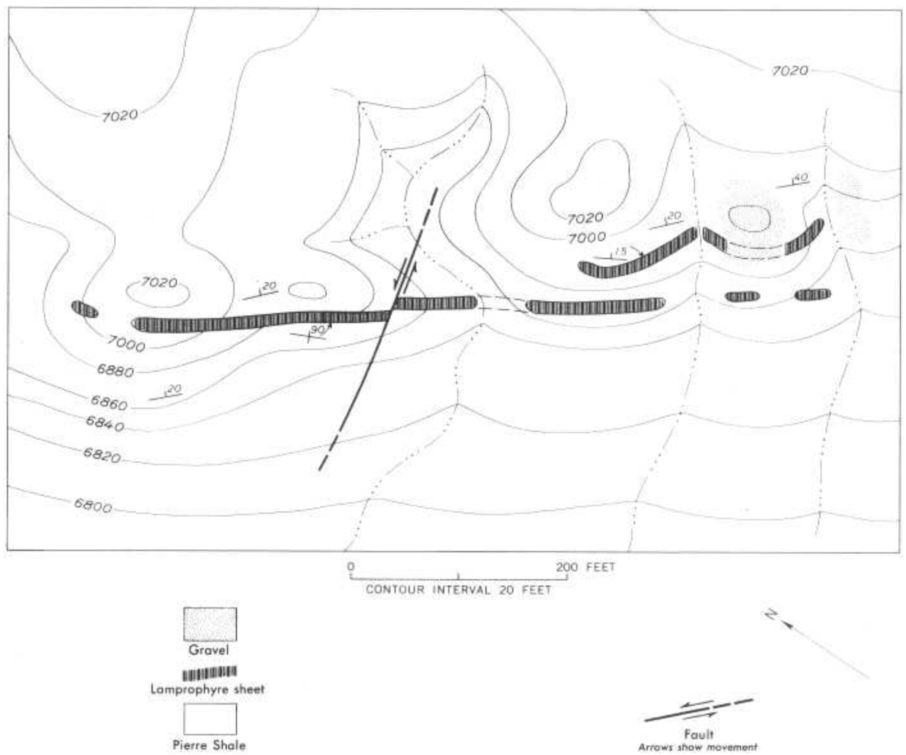
On the north side of Ponil Creek Trail 0.2 mile above the gaging station is a small but impressive example of still another kind of fault: a reverse fault that has very low dip (fig. 112). This fault, which dips 15° upstream, or northwest, has broken across at least three sandstone beds and a coal bed in the Vermejo Formation and has shoved these layers 17 feet southeastward along the fault, so that they are repeated in the roadcut. The hard sandstone beds have broken and moved cleanly, but the soft coal is contorted and dragged out where the fault crosses it. There is no way to be sure whether the upper rocks were pushed over the lower ones, whether the lower were pushed under the upper, or whether both sides moved a little. All we can be sure of is the relative movement, which consisted of telescoping or thrusting. For this reason, such low-angle reverse faults are called thrust faults.

Some of the world's great faults are thrusts in which plates of rock hundreds of miles long and thousands of feet thick have been shoved tens or even hundreds of miles over other rocks. The Rocky Mountain front for at least 350 miles in western Montana and southern Canada is a zone of thrust faults in which rocks as old as Precambrian have been thrust as much as 75 miles eastward over rocks as young as Late Cretaceous. Even larger thrusts are known in Nevada. The British Isles, and the Alps too, are riddled with huge thrust faults.

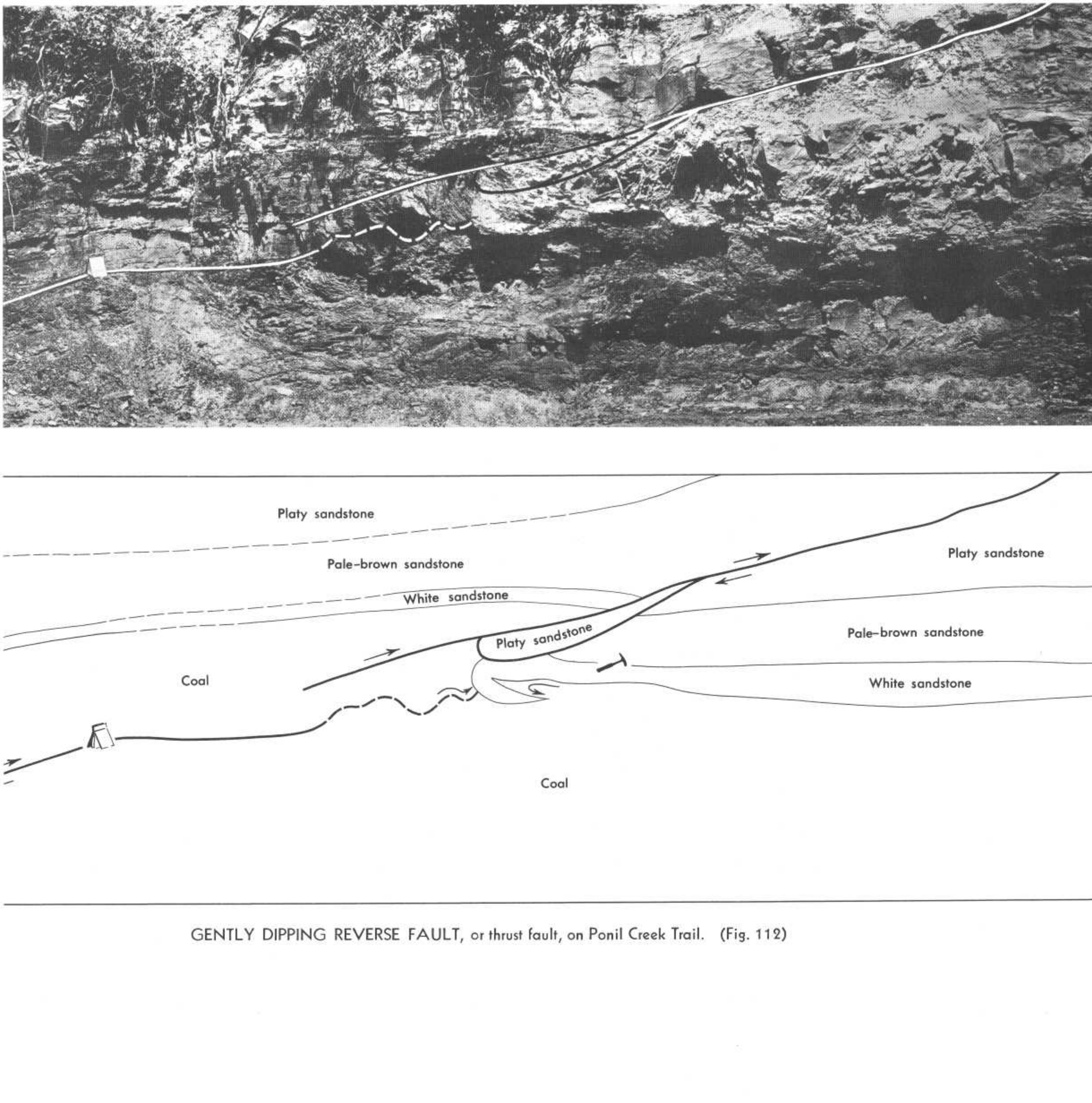


HORIZONTAL OFFSET OF DIPPING BEDS by vertical movement. A, Dipping beds before faulting. B, Vertical movement on steep fault that cuts across the strike. C, Erosion of uplifted side, leading to false appearance of horizontal movement. D, Stream canyon cut along fault, so that the V's formed by outcrops of beds now point downstream. This may have happened on the Abreu fault. (Fig. 109)

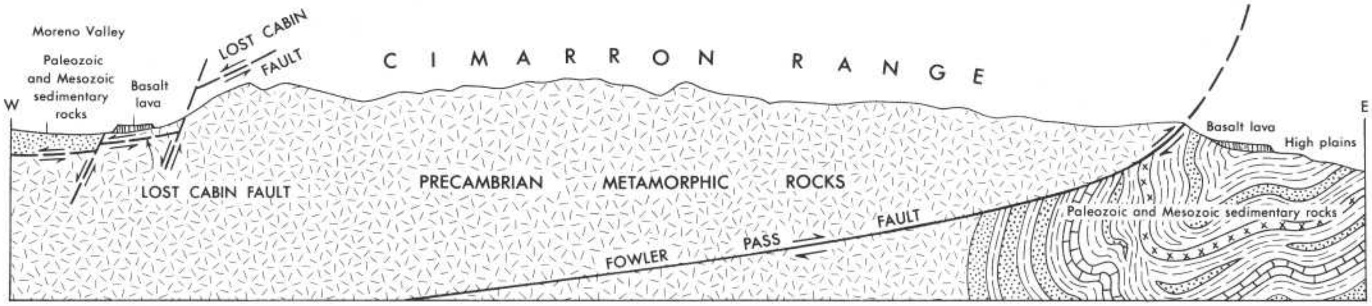
FAULT, along which movement was horizontal, cutting vertical lamprophyre sheet and moderately dipping Pierre Shale on Horse Ridge. Geologist is standing on the fault. The sheet has been offset 7 feet, which happens to be just about its thickness; the rocks on the left have moved toward the viewer, and those on the right, away. There may have been some vertical movement also, but because the sheet itself is vertical this cannot be detected. (Fig. 110)



GEOLOGIC MAP of lamprophyre sheet in Pierre Shale on Horse Ridge. Fault along which movement was horizontal is in center. (Fig. 111)



GENTLY DIPPING REVERSE FAULT, or thrust fault, on Ponil Creek Trail. (Fig. 112)



FOWLER PASS AND LOST CABIN FAULTS viewed as the sides of a giant plunger of Precambrian rocks thrust northeastward under what are now Moreno Valley and the Cimarron Range and exposed by later uplift and erosion. (Fig. 113)

Thrust faults are reverse faults that have a low dip, and some faults that are steep reverse faults at the surface flatten to thrusts at depth. Is it possible that the Fowler Pass and Lost Cabin faults are such concealed thrusts, having horizontal displacements of many miles, rather than steep reverse faults, having vertical displacements of a few thousand feet? Supporting this glamorous idea is geologic mapping in the Moreno Valley to the west (fig. 113). There the same Paleozoic and Mesozoic formations as are exposed at Philmont seem to be in faulted contact with the Precambrian crystalline rocks, and the fault surface seems to curve gently at shallow depth beneath the valley. One way to tie this surface to the contact of sedimentary and metamorphic rocks on both flanks of the Cimarron Range is to picture a giant plunger of Precambrian crystalline rocks thrust many miles northeastward under and partly through a blanket of younger sedimentary rocks and now exposed by uplift and erosion. There are other ways, however, to explain the field relations (see pls. 5, 6), and this bold thought must remain as just a thought until it can be tested by much more detailed work.

In a few paragraphs we have worked our way from a small unexciting fault on Ponil Creek to a sweeping idea that may or may not explain the general structural pattern of the entire Cimarron Range and its bordering valleys. The idea may not survive, but at least it shows what intriguing possibilities there are in applying geologic ideas, based on observation, to larger features whose full dimensions are hidden.

Large and old faults like the Shaefers Pass and Fowler Pass faults do not often advertise themselves. The actual break is usually hidden by fallen rock or by soil, and signs of movement such as scarps or offset stream courses are destroyed or are covered by deposits younger than the faulting. To recognize a fault takes thorough knowledge of the rock sequence and careful tracing of formations on the ground. The result is rewarding, if unraveling puzzles like this appeals to you, but the structure is usually not much to look at: it is too big to see without reducing it to smaller scale by mapping.

Two other faults that are too big to see are shown and named on the geologic map—the Beard fault, in the northern benchlands, and the Sawmill Canyon fault, along the mountain front west and south of Ute Park. Detailed mapping would surely reveal others. They are mostly steep faults that bend little as they cross rough country. None have had more than a few hundred feet of movement, so that only a formation or two is cut out or repeated.

On the map the relative movement on faults is shown by the letters "U" for up and "D" for down. Usually there is no way of knowing the actual movement with relation to a fixed surface, such as sea level. On some faults, both sides may have moved in the same direction but different amounts.

Without knowing how the rocks actually moved along a fault, we can figure out the offset of the two sides in several ways. A quick guess can be made by noting the thickness of formations that are cut out or duplicated by the faulting, taking their dip into account; this is the method we have been using in our discussion. A much better estimate can be reached by making a drawing to scale and measuring the offset. On most faults there is both horizontal and vertical displacement, so that the total movement is oblique.

Generally, the main movement on faults everywhere, as at Philmont, seems to be vertical. Nevertheless, tremendous amounts of horizontal displacement are known on some faults elsewhere, if not at Philmont. For example, the vertical San Andreas fault in California, which has been traced for at least 600 miles and may be much longer, seems to have had at least 30 miles of horizontal offset in the last few million years and as much as 400 miles of total horizontal offset since late Mesozoic time; never has it had more than a few hundred feet of vertical movement. The movements which add up to this startling displacement were not in a few gigantic shoves but in thousands of small shifts coming many years or centuries apart. One such movement caused the famous San Francisco earthquake of 1906 in which the maximum horizontal offset was 21 feet. Great total vertical displacements, too, are the result of many small movements rather than of single great ones; the largest vertical displacement known in a single fault shift was at Yakutat Bay, Alaska, where a part of the coast rose nearly 50 feet in 1899.

On some faults not even the relative movement can be learned. For instance, we cannot say anything about movement on the faults that border the mass of coarse-grained granodiorite near Clear Creek Store. That the borders are faults is plain for both the granodiorite and the metamorphic rocks are crushed and broken in a belt several hundred feet wide along each border; but without knowing the relation of the metamorphic rocks to the granodiorite before faulting, we have no way to tell how the faults moved. However they moved, they formed before the Sangre de Cristo Formation was deposited, as the Sangre de Cristo rocks lie across both faults and show no sign of disturbance. These faults are certainly no younger than Pennsylvanian and may well be Precambrian.

The metamorphic rocks are doubtless broken by many other faults that were active both before and after metamorphism, but we do not have the information to recognize and interpret them.

Philmont in three dimensions

Now that we have some idea of the main disturbances—the folds and faults—that affected the layer cake, we can start thinking of the geology of Philmont in three dimensions. This has been done in detail for three slices, or cross sections, across the region, roughly at right angles to the main structural trends, on plate 5 (in pocket) and in less detailed but more digestible form on the familiar block diagram (plate 6, in pocket). Because of vertical exaggeration, the dips of formations on plate 6 look steeper than those of the same formations on plate 5, which shows the same slices at natural scale.

These illustrations, especially cross section *C*, show vividly the broad anticlinal arch that is the main structure of Philmont and its oblong core of metamorphic rocks and granodiorite that has been dragged up the sedimentary formations on its flanks and punched through some of them. Beyond the core, the cross sections show the folds into which the solid sedimentary rocks have been bent: broad shallow ones in the Tertiary rocks, narrower and deeper ones in the older rocks.

The diagram and sections reveal the main unconformities, between the Precambrian rocks and the Sangre de Cristo Formation, between the Vermejo Formation and the Raton Formation, between the Poison Canyon Formation and the loose Quaternary deposits, beneath the basalt flows, and between the basalt and the loose Quaternary deposits.

Displayed, too, are the relations of the porphyritic igneous rocks. Sheets of them invade the metamorphic rocks of the mountain core, follow some of the faults, and spread through the sedimentary layers, both along and across the beds (more about these later). Visible also is a generation of steep faults that break through the complex of sedimentary layers and igneous sheets; some of these faults no doubt served as conduits through which the basalt lava rose to the surface.

Reviewing what we have seen of folds and faults and what we have reasoned about them, we realize that at Philmont they are not scattered at random but have a fairly clear pattern in space and in the fourth dimension, time. The rocks beneath the plains are gently folded and are broken only by small faults distinctly younger than the folds. The intensity of folding and faulting increases toward the mountains and is at a peak near the contact between Precambrian metamorphic rocks and the much younger sedimentary and igneous rocks. Here, also, faulting is younger than folding, but probably not much younger.

Two main times of deformation are evident: one, about which we know little but suspect much, in Precambrian time; the other, spread over a long fraction of Tertiary time after the Poison Canyon Formation was laid down but before the basalt lava poured out. Only a little faulting and tilting has come after the lava.

No movement has occurred on any of the faults since the region has been settled and probably not for many hundreds or thousands of years. Earth movements convulsive enough to break the ground are accompanied by major earthquakes. Neither history nor legend reports any great quakes in the Philmont region, nor are there any fresh signs of movement—such as scarps, long sag ponds, or offset streams—along known faults.

Uplift

About half the mapped sedimentary formations of Philmont were formed in the sea and half on land. In succession, the Sangre de Cristo, Dockum, Entrada, and Morrison were laid down on land; the Dakota, near and in the sea; the Graneros, Greenhorn, Carlile, Niobrara, and Pierre, in the sea; the Vermejo, partly on land and partly in the sea; and the Poison Canyon and Raton, on land. All the still younger unnamed formations were also deposited on land. Why did the sea come in and go out? And how did Philmont, which spent most of Mesozoic time near or below sea level, come to be much more than a mile above the sea today?

Has the level of the sea repeatedly risen and fallen hundreds, even thousands, of feet, or are earth movements responsible? Based only on observations at Philmont, we cannot hope even to begin answering this question or a long series of others that logically follow from it. To get the flavor of the problem, we need only remember that if sea level has changed on a large scale, it could not have been merely a local affair but had to be worldwide, for the oceans are all connected. Just to start working on the question would require nothing less than a sampling of the geology of the world, complete with accurate dating throughout, to decide whether submergences and emergences at Philmont coincided with worldwide shifts in sea level or whether they alternated due to more localized earth movements through geologic time. But not nearly enough absolute dates are known, as our earlier discussion of radioactivity dating pointed out, to make this possible now.

If direct human experience is any guide, the odds favor earth movements. Careful measurements prove that some parts of the earth's surface are now rising while others are sinking with relation to sea level, usually at rates of a few inches to a few feet in thousands of years, and historic records show that this rate of movement has held for at least 3,000 years. On the other hand, there has been no detectable change in the volume of the sea and, therefore, no change in sea level in historic time, but there is really very little information with which to work.

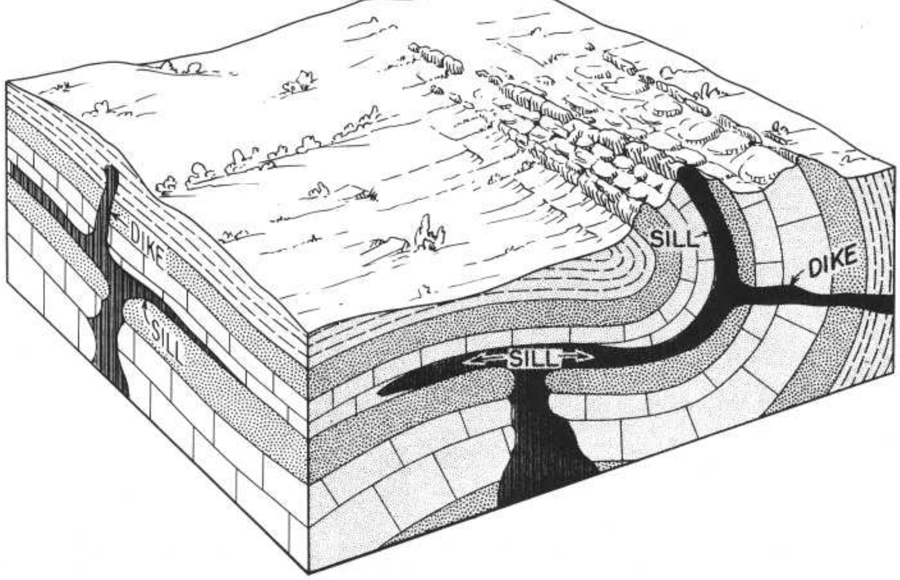
Indirect evidence, however, indicates that the sea itself has risen and fallen, not far back in time. Worldwide rise and fall of sea level amounting to several hundred feet in earlier Quaternary time is strongly suggested by both raised and submerged beaches that have been traced for thousands of miles on several continents and around oceanic islands. These major changes in the total volume of sea water reflect the alternate growth and melting away of several ice sheets of continental size that left their deposits and scars over much of North America, Europe, and Asia. When a large fraction of the earth's water was locked on land as ice, sea level fell; when the glaciers melted, sea level rose.

Worldwide sea level has no doubt been changed in this way, and more than once, but it is not a very useful general explanation of shifting shorelines in the geologic past: in every geologic period there have been major shoreline shifts somewhere, but for only two other times before the Quaternary—in the Permian and in the late Precambrian—is there any evidence of continental glaciation.

If earth movements were responsible for alternating land and sea at Philmont, they were not folding or faulting of the sort we have recognized, except perhaps for final emergence at the end of Vermejo time. Had the sea been let in by downfolding or downfaulting or been forced out by rising folds or fault blocks, such events would be signaled by marked angles between the tilted bedding in the deformed rocks and flat bedding in later rocks. This angle would remain even if the later rocks themselves were deformed. The small angle between the Vermejo Formation and the Raton and Poison Canyon Formations indeed suggests that actual uptilting on the west forced the seashore to retreat eastward at the end of Cretaceous time, but there are no similar signs of deformation to fit the other land-sea oscillations. Indeed, the largest structural events in the last 500 million years seem to have been the folding and faulting that occurred after Poison Canyon time, when the area had long been out of the sea. And even those disturbances can hardly explain the rise of the entire region to its present altitudes. Arching and upfaulting might have brought the Cimarron Range to its present heights, but the plains to the east are far more than a mile above the sea without benefit of recognizable upfolding or upfaulting.

Vertical uplift accompanied by little tilting and on a grand scale seems to be the only answer to the tremendous gain in altitude since Poison Canyon time. It may also explain some of the sea-land shifts of the more distant past. Such wholesale uplifts are part of the geologic record in many parts of the world and at many times in the geologic past.

DACITE PORPHYRY SILL. Light-colored ridge in center is sheet of dacite porphyry intruded parallel to bedding of sedimentary rocks. Across U.S. Highway 64 from Ute Park. (Fig. 114)



SILLS AND DIKES. Sills follow bedding; dikes cut across bedding. (Fig. 115)

Injections of molten rock

Another kind of dynamic underground process was at work in the rise of every body of igneous rock into the Philmont cake. Knowing almost nothing about the igneous bodies in the Precambrian rocks, we will look only at those in the sedimentary rocks. These igneous rocks made their way upward by either spreading the bedded rocks apart or shoving them bodily away. They certainly did not melt their way up; in fact, they scarcely heated the invaded country, for sedimentary rocks of all colors and kinds are little changed near all but the largest igneous bodies, except for discoloring or hardening within the first inches or feet from the contact. Thus, the intrusion or injection of molten rock has mostly been mechanical: in some way, solid rocks have been moved aside to make room for hot sticky liquids.

Nearly all the many igneous bodies at Philmont are sheetlike, and the sheets are nearly all parallel to the bedding of the sedimentary rocks (figs. 32, 114). Such intrusions along bedding are called sills, another ancient British mining term. Where strata dip steeply, as along the mountain front, sills dip steeply also; where the enclosing beds lie almost flat, as in the northern benchlands, so do the sills, as figure 115 illustrates. Most of the sills are dacite porphyry; a few are andesite, and still fewer are diorite.

The sills are nearly all in shale. Some merely wedged their way in by spreading the shale apart. Others, remarkably, seem simply to have taken the place of the shale. For example, the Dakota Sandstone consists of two sandstone ledges separated by about 100 feet of shale; but in southern Philmont the shale is displaced by dacite porphyry, and for many miles along the mountain front the entire space that should be oc cupied by shale is filled by dacite porphyry, jammed against sandstone on either side.

Where did the shale go? The dacite was not hot enough to metamorphose the sandstone, and it has scarcely a fragment of shaly rock floating in it. The dacite probably did not melt and digest the shale, nor did the shale, which is lighter in weight than the dacite, sink away mysteriously in the depths. Most probably, the shale was partly pushed by the pasty melt and partly floated upward on it above the present level of exposure. An interesting speculation is that, with the help of steam rising from the cooling dacite melt, the shale might have been forced out at the surface to form mudflows that resembled the Quaternary landslides. If so, these rocks were removed long ago by erosion, as they were formed far back in Tertiary time, and no remnant of the land surface at that time is now preserved.

Although most of the intrusive bodies are sills, it is obvious that any melt rising from deep below the sedimentary layer cake must cut across lower layers to get into rocks high in the pile. (See fig. 115; pls. 5, 6.) A few of such crosscutting sheetlike bodies, called dikes, can be seen at Philmont. The largest are in the northwest corner, but these are hard to reach. Interestingly, most of the dikes are andesite and lamprophyre; only a few are of dacite porphyry. This is surely no mere accident but reflects some difference in the age or origin of the various intrusive rocks—what, we do not yet know.

The most accessible dike is the lamprophyre dike on the south side of Horse Ridge. (See figs. 31, 110.) It stands vertically, cutting boldly across shale beds that dip about 20° N. Here we see how dikes may turn and become sills, for that is exactly what the dike does on the east (right) side of the gulch shown in figure 31*A*. Figure 116 is a diagram of this dike-sill. Another easily reached though very small dike, of dacite porphyry, is in the Morrison Formation exposed on Cimarroncito Creek 1.3 miles upstream from the turnoff to Cimarroncito Base Camp. (See fig. 86.)

Tooth of Time Ridge (fig. 117) is part of a sill, but it is a special kind, for its base and top are not roughly parallel; instead, the top is domed up like the cap of a mushroom. Such thickened sills, which seem to have arched their roofs, are called laccoliths (fig. 118). As figure 118 reveals, Tooth of Time Ridge is really a double-deck sandwich made of two laccoliths. The upper one shoved in along the base of the upper part of the Niobrara Formation, and the lower one shoved in at the top of the Carlile Shale, leaving the Fort Hays Limestone Member between. The domelike shape of the whole structure is well shown by the form of the outcrop of the Fort Hays Member, which makes an outward dipping loop about 2½ miles long from east to west and 1½ miles wide from north to south.

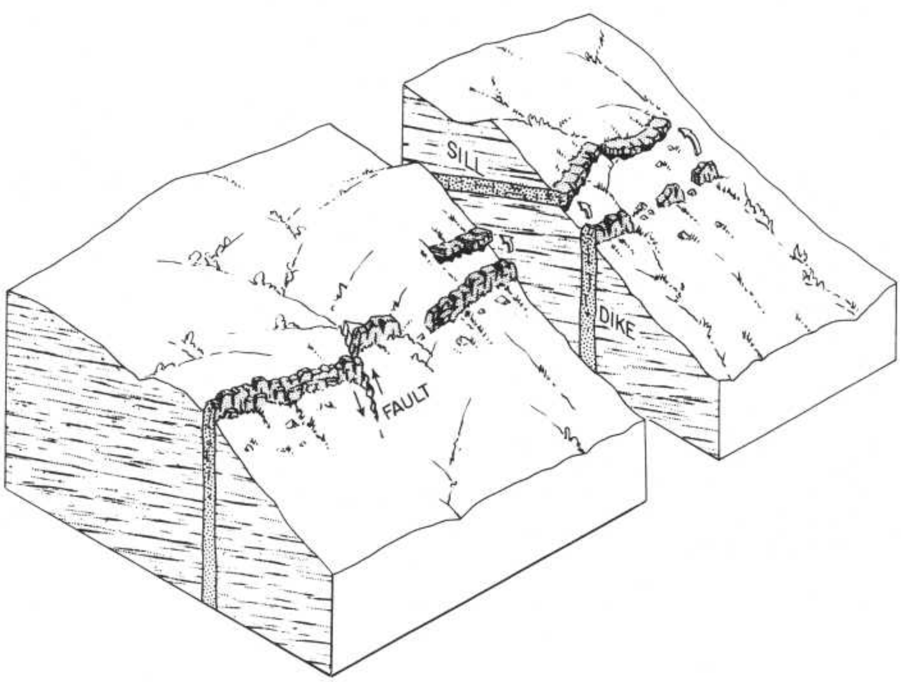
Some laccoliths may have complete mushroom shapes, including stemlike feeders at the base; but many have feeders at the sides, through which the molten rock was injected like toothpaste from a tube. We suspect but cannot prove that this is true of the Tooth of Time laccoliths.

About 30 square miles of high country between Baldy mining camp and Cimarroncito Peak is underlain by a swarm of overlapping laccoliths, to judge by the complicated outcrop pattern of alternating stripes of sedimentary rocks and of dacite porphyry. The peaks seem to be on the crests, or thickest parts, of the largest laccoliths. Such many-storied laccoliths are often called Christmas-tree laccoliths.

At Philmont we cannot tell how the myriad sills were fed. Laccolith swarms in a few other parts of the world, such as the Henry Mountains of Utah, however, are exposed enough to show that their laccoliths were fed mainly from the side by a few large torpedo-shaped masses, called stocks, that extend downward into the earth's crust. Feeder stocks, in turn, may be merely bumps on really huge masses of granitelike rocks, called batholiths, that lie still lower, but no more than 10 to 20 miles down. Possibly, several feeder stocks underlie the Cimarron Range, and they may pass downward into a batholith. Several batholiths having stocks on their backs that radiate sills and laccoliths are exposed farther north along the Rocky Mountain chain, so there is more than just vivid imagination to this idea.

The squeezing, however quietly and slowly, of many cubic miles of molten rock into a small segment of the earth's layered skin was a tremendous dynamic event. It is natural to wonder if this event may not have been closely related to the dynamic events of folding and faulting. The general time relations encourage us to think so. Except for the slightly metamorphosed granodiorite and diorite porphyry which are probably of Precambrian age, all the intrusive igneous rocks of Philmont are of Tertiary age; they are younger than the Poison Canyon Formation but older than the basalt. The same is true of nearly all the known folds and faults. Involved, however, is a fairly long stretch of time, perhaps as much as 50 million years. To narrow the time interval we must look at places where structures and intrusive bodies meet.

The evidence from places where sills meet folds is of little use. True, the sills follow the curve of folded beds, but they might do so whether older, younger, or the same age as the folds. The



LAMPROPHYRE SHEET at Horse Ridge. Sheet is mostly dike but partly sill. (Fig. 116)

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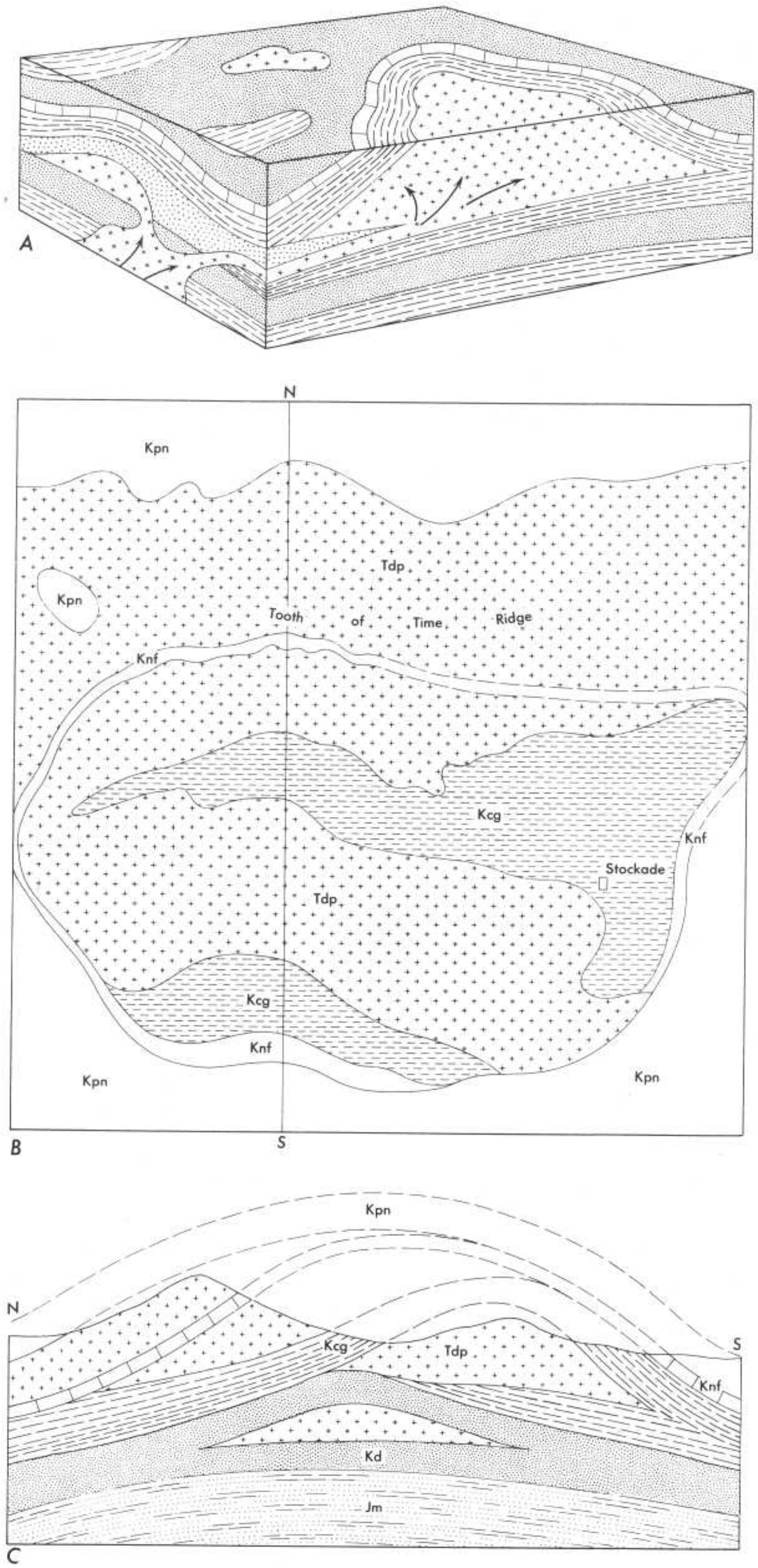
THE TOOTH OF TIME, viewed north from the Stockade on lower Urraca Creek. The Tooth is a spectacularly weathered outcrop of the dacite porphyry double laccolith of which Tooth of Time Ridge is a part. (Fig. 117) straight dikes in folded rocks, as in the northwest corner of Philmont, certainly are younger than the folds; if the dikes are the same age as the sills, then the sills too are younger than the folds.

The relations between faults and intrusives are clearer but even more complex. The Fowler Pass fault is older than the dacite intrusions that obliterate much of it, but the steep Beard fault that goes from Dan Beard Trail Camp to South Ponil Creek cuts and is younger than the great dacite sill of the northern benchlands; and the Sawmill Canyon fault that curves from Maverick Creek, west of Ute Park, nearly to Cimarroncito Base Camp cuts and is younger than several dacite sills. Faulting and the rise of magma into the Philmont cake, therefore, overlapped not only in space but also in time. As the faulting is younger than the folding—but not very much younger—we conclude that Tertiary deformation and intrusion at Philmont were indeed intimately linked.

Just how they were linked is a mystery. It seems clear that the laccoliths pushed up their roofs, but there is certainly not a laccolith to account for every anticline. And how can we account for synclines and for the Cimarron Range itself? There seems to be no superlaccolith beneath the largest anticline of all. Perhaps magma in general does not force its way into the crust but rises quietly where the crust is bulging and rock pressure is therefore low. We do not know enough to justify further speculation.



LACCOLITHS: thick sills that have arched their roofs. A, Sketch of ideal laccolith. B, Simplified geologic map of Tooth of Time Ridge: part of a double laccolith. C, North-south slice across Tooth of Time Ridge. Tdp, dacite porphyry; Kpn, Pierre and Niobrara Formations; Kog, Carlile and Graneros Shales; Kd, Dakota Sandstone; Jm, Morrison Formation. (Fig. 118)

Volcanic eruptions

The lava flows and bomb beds give the most vivid and direct evidence of subterranean processes that have been at work at Philmont. The molten rock which made them came to the surface through some sort of openings. We do not know where the openings were that fed the thick pile of flows on Ocaté Mesa or what their form may have been—whether they were pipelike and surrounded by a conical pile of erupted material, as is the familiar volcano, or whether they were long fissures and never had a cone shape. But the basaltic rocks that cap Crater Peak, Rayado Peak, Fowler Mesa, and Urraca Mesa were probably erupted from a short-lived volcano that stood a little south of the present Crater Peak. Its surface cone, if it ever had much of one, has been worn away, but the remnants of a small steep-walled flat-floored crater can be seen on the southwest flank of Crater Peak (fig. 119); its feeder has not been found. Most likely the crater was fed through a pipe that has been eroded away or is not yet exposed; but possibly the feeder really is at the surface, partly concealed by slide rock and trees, waiting to be discovered.

The crater filling is just behind the buffalo-head shape of Crater Peak, as seen from the plains north of Rayado Creek (fig. 120).

When the volcano was active, Rayado Creek did not exist, or at least was not very deep. If it had been, the basalt, a tough resistant rock in this climate, would be found far down the valley walls. Surely, then, the volcano ceased to be active long ago. Volcanoes are most likely to break through at the surface along fault zones, especially at the intersection of faults having different trends, so it is no surprise to find a volcano near the intersection of the Fowler Pass fault and the concealed fault that probably controls the course of Rayado Creek. Remember that the Fowler Pass fault dips west, right under the volcano, but is older than the volcano, as lava erupted from the volcano crosses the fault without offset.

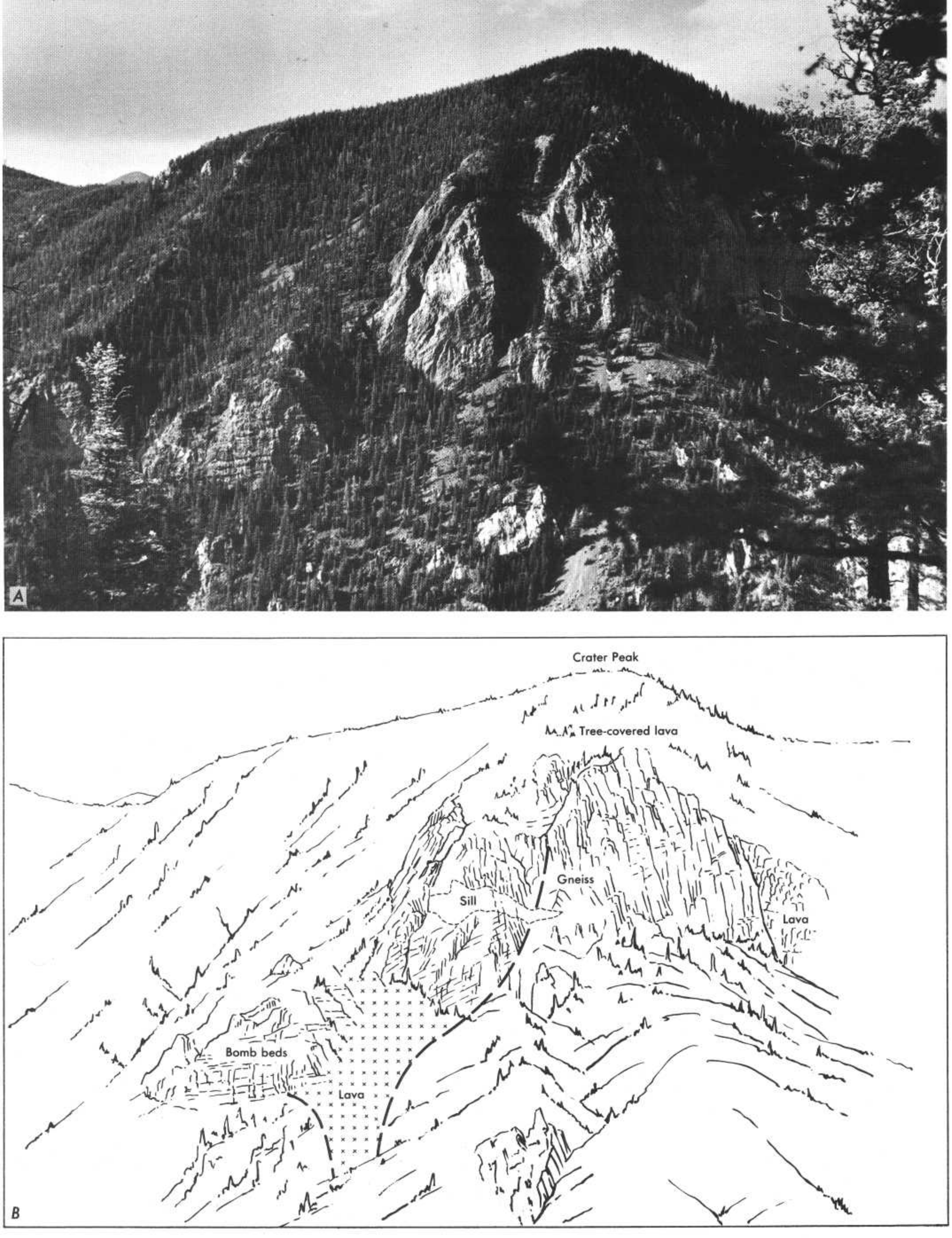
Ground water in folded rocks: Artesian water?

Earlier, in considering ground water, we feared that the present sources of water—streams, lakes, reservoirs and shallow wells—might not be able to support much expansion of ranching and camping even if energetically developed; and we wondered if large sources of water, perhaps under pressure, might not exist deep beneath the thirsty plains. But without knowing about the distribution, sequence, and structure of possible water-bearing rocks, we could not pursue the matter. Now we can.

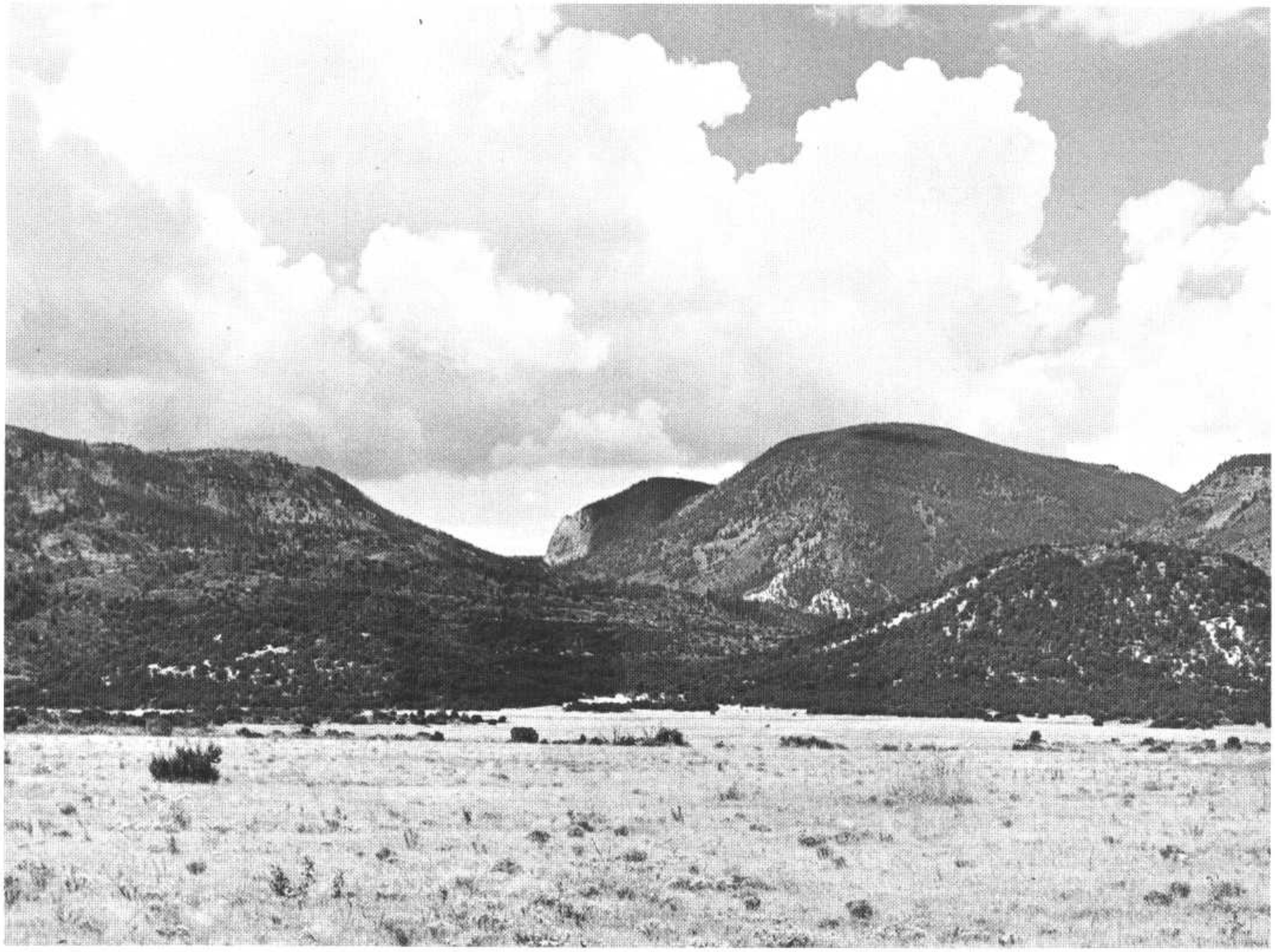
Only rocks made of sand and gravel and having large connected pores are likely to be good carriers of water, or aquifers. At Philmont such rocks are abundant in the Sangre de Cristo Formation, Dockum Group, and Entrada, Dakota, Trinidad, Raton, and Poison Canyon Formations. But most of these were laid down rapidly by rivers on land: fine particles of clay and mica were not washed out, and the pores tend to be clogged; further, the individual sandstone layers, though in places very thick, probably do not continue very far but are lenses surrounded by shale. Many poor or dry wells already drilled in the Poison Canyon and Raton Formations show that these units are not promising aquifers; there is no reason to think the stream-laid Sangre de Cristo or Dockum rocks would be any better. This leaves the cleaner, more uniform and rounder dune or beach sandstones of the Entrada, Dakota, and Trinidad Formations.

To supply much water over a long time, our imagined aquifers must not only hold much water but must crop out where there is plenty of rain and snow for recharge—that is, in the mountains. This rules out the Trinidad which was eroded from the mountain area before the Raton Formation was deposited and crops out only in the northern benchlands. But the two thick sandstone layers of the Dakota, 100 feet apart, and the Entrada Sandstone, 400 feet lower, are still in the running. Indeed, the Dakota seems to be a winner, as it is a known major aquifer far out on the plains, where thousands of producing wells have been drilled in it.

Where they crop out along the relatively rainy mountain front, the Dakota and Entrada dip rather steeply eastward. Almost certainly, they flatten out beneath the benchlands to the north and the plains to the east (see the structure model, pl. 6, and the geologic sections, pl. 5), but nevertheless they are far beneath places where much new water is likely to be needed, as at the base camps of the Scout Ranch. The top of the Dakota Sandstone is probably about 4,000 feet beneath Ponil Base Camp, less than 2,000 feet beneath the Camping Headquarters, about 1,000 feet beneath Carson Maxwell Base Camp, and perhaps as little as 800 feet below New Abreu Base Camp. Add about 550 feet to reach the Entrada.



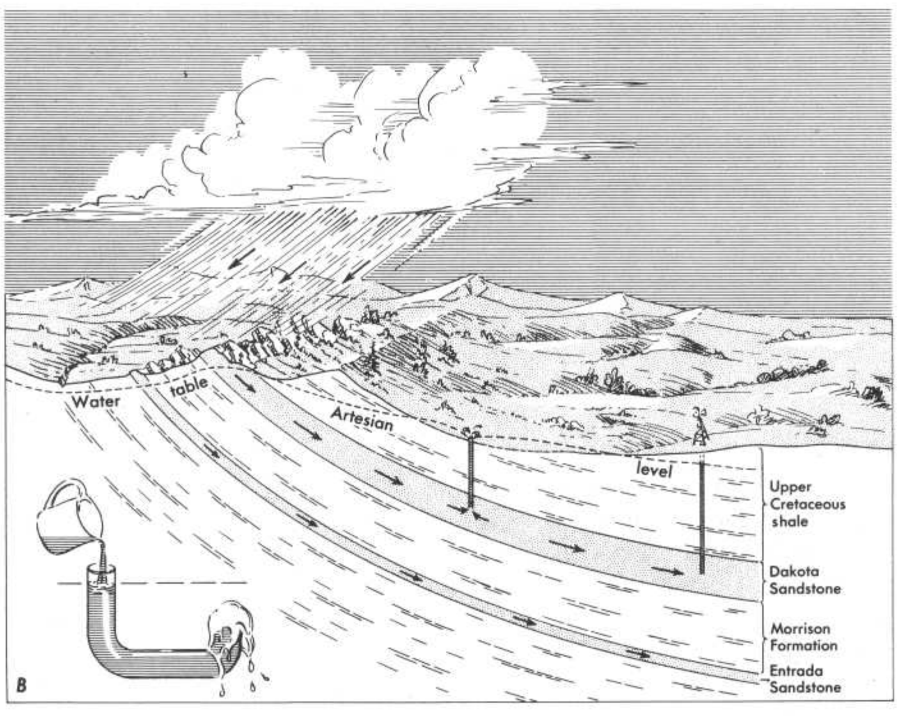
CRATER PEAK, an eroded volcano. A, View from the south. B, Geologic sketch. (Fig. 119)



CRATER PEAK, viewed from the plains north of Rayado Creek, has the shape of a buffalo head. The face is light-colored Precambrian gneiss; the hairy cranium is basalt. Just beyond the face, hidden from view, is the eroded crater that gives the peak its name. (Fig. 120)

Some day the trial will be made, possibly as a side issue in drilling for oil. When it is made, there is a good chance that abundant water will be found in both the Dakota and the Entrada and that the wells will be artesian—that is, the water will rise far above the aquifer, though probably not to the surface, without pumping. A good reason is that the flowing artesian well at Ute Park mentioned earlier is in the Dakota Sandstone (fig. 121). The unimpressive-looking trickle of water in the photograph is really the top of a water column 167 feet high, pushed up by its own pressure from its source in the Dakota, which crops out only 500 feet to the West.

Why does the Dakota yield artesian water? Figure 121*B* may help explain. Water entering the Dakota Sandstone and flowing down the dip to fountain out at Ute Park or to rise high in wells under the plains may be compared to water poured into a J-shaped tube. As everyone knows, a little water poured into such a tube will rise to the same level on both sides; if the water level in the long arm is kept higher than the top of the short arm, a fountain results. If the tube is filled with sand, the situation is not changed very much except that the water will not rise as high or as rapidly in the outlet side because of the frictional resistance of the sand grains. In our natural artesian system, the long intake arm of the tube is the outcropping Dakota Sandstone, the walls of the tube are the impermeable shales that lie above and below the Dakota, and the short outlet arm is a well.



ARTESIAN WATER at Philmont. A, Flowing artesian well, 167 feet deep, at Ute Park. B, Possible artesian flow from the Dakota and Entrada Sandstones. (Fig. 121)

SHAPING THE LANDSCAPE

So much for the tortured inner life of the Philmont cake during the past billion years or so. But what was happening on the surface while metamorphism and intrusion, folding, faulting, and uplift were going on below? We have had many hints along the way. Now to concentrate on the landscape and how it has evolved.

The scenery of Philmont, as we saw early, is made up of seven main elements, which are shown on the landform model (pl. 1): (1) steplike gravel-capped lowland plains which in most of Philmont flank the main streams in narrow belts but spread out to cover the southeastern part; (2) high steep-sided flat-topped hardrock benchlands that make almost the whole northern half, the southern edges, and a few scattered surfaces between, such as Deer Lake Mesa, Antelope Mesa, Urraca Mesa, Fowler Mesa, and Crater and Rayado Peaks; (3) rough hummocky hillsides along much of the mountain front and around the benchlands south of Cimarron Creek and in Ute Creek Valley; (4) rugged mountain country, without flatlands, in the western part; (5) high swampy meadows in the southwest corner and along Bonito and Agua Fria Creeks; (6) a network of streams that flow away from the crest of the Cimarron Range and join Cimarron Creek, which flows across the range; and (7) scattered natural lakes, most of which are on the high meadowlands.

We also realized that running water has been doing most of the work of carving the landscape, but just how the carving is done and why the scenery is very different in different parts of Philmont were mysteries. Now that we know something of the rocks beneath the land—how and when they were formed and how and when they were deformed—some of the mystery can be cleared away. To understand the scenery, look underneath the greenery.

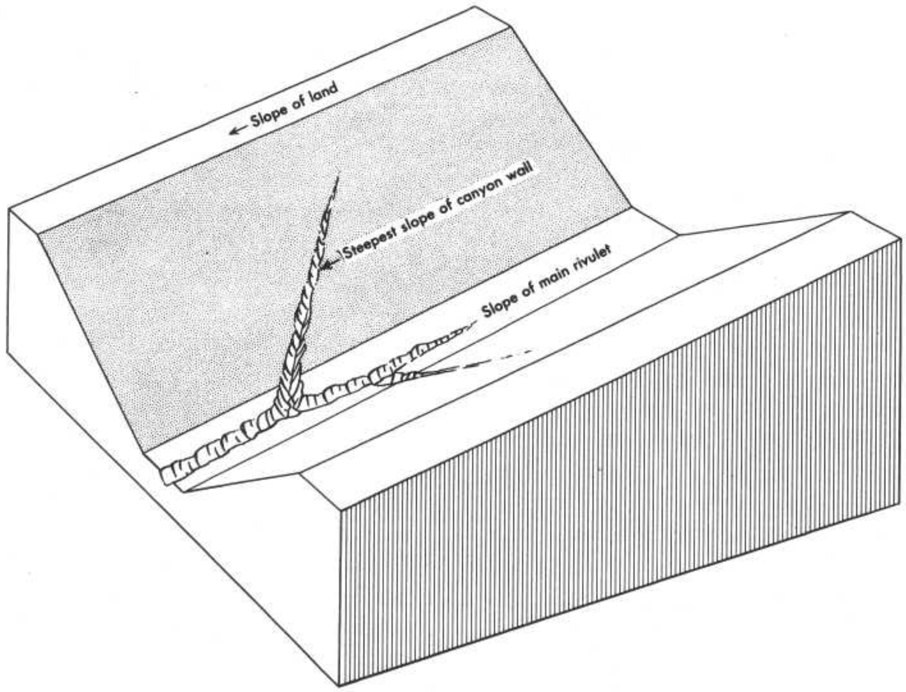
Compare the landform model (pl. 1) with the geologic model (pl. 4). Clearly, the larger landscape features are closely related to the underlying rocks and their structure. Beneath their veneer of sand and gravel, the broad lowland plains are underlain almost entirely by the soft shale formations of Late Cretaceous age: Graneros, Carlile, Niobrara, Pierre. The high benchlands are carved in hard rocks that have low dips or are flat. The northern benches are cut in sandstones and conglomerates of the Trinidad, Raton, and Poison Canyon Formations and in one great sill of dacite porphyry. The southern benchlands are cut in sheets of basalt. Long narrow ridges that stick out of the plains and benchlands are dikes of dacite porphyry, andesite, or lamprophyre. The hummocky hillsides appear only below steep hillfronts that expose shale, mostly the Pierre Shale. The rugged mountain front is carved on the upturned edges of alternate hard and soft folded and faulted rocks: the ledges are made mainly of dacite porphyry and of sandstones of the Sangre de Cristo, Dockum, Entrada, and Dakota; the valleys are are in soft shales of half a dozen formations. The mountain core is Precambrian metamorphic and igneous rocks. The streams flow away from the mountain core, which has been lifted up in a great arch. The swampy high meadows and natural lakes are nearly all on lava flows.

It may be interesting to look more closely at how running water and geology have combined to make each of the seven kinds of landforms. We will begin with the stream network.

The network of streams

The Cimarron Range was slowly arched up many thousands of feet in middle and late Tertiary time, and the large streams drain away from its crest simply because they are flowing downhill. The range itself, unlike many ranges, does not exist because of stream sculpture but in spite of it. The streams are destroying the range but have a long way to go. A look at the landform model and at the streams themselves shows that they are doing their destructive work not only by cutting both downward and sideways but also by growing longer and by adding tributaries. They have been doing this from both sides long enough to score the range deeply and to narrow its crest but not long enough to make sharp peaks—the summits are flat rather than pointed. The pattern the streams have made is like a great oak leaf, having Cimarron Creek as its stem: each stream junction is a V pointing downstream, except along the mountain front between Cimarroncito Creek and Ute Park Pass, where the large tributaries run parallel to the front and to each other, like a trellis.

How a leaflike, or treelike, drainage pattern starts is easy to observe at Philmont. Watch what happens in a heavy rainstorm to any smooth but sloping surface underlain by loose sand or soft shale, such as one of the drainage ditches along Highway 21 or the front of a bench on the lowland plains. At first the whole surface may be flooded by a sheet of water that soon becomes muddied by bits of shale. As the storm continues, the rushing water begins to scoop out the softest places, and tiny rills start to form parallel to the slope; once formed, such rills tend to deepen fast and become fixed because they are low places toward which more and more water flows. Soon some of the rills become rivulets, running in miniature V-shaped canyons. Then, in the same storm or later, tributary rills start to grow by branching from the rivulet and cutting back into the walls of the little canyons (fig. 122) not at random but angling downstream. This is because the tributary grows in the direction of fastest flow, which is down the steepest slope of the canyon wall. If the main rivulet had no slope, the path of the tributary rill would be at right angles to it; but the rivulet slopes downstream, so the steepest path for a tributary is not at right angles to it but slanting downstream. Before long the surface is cut up by a network of branching gullies, as in this view (fig. 123), just upstream from Webster Reservoir, of a lowland bench just starting to be dissected.



HOW LEAFLIKE DRAINAGE PATTERNS are formed by streams starting on smooth and uniform rock. Tributaries grow not at random but angling downstream, in the direction of steepest slope of the valley walls of the main stream. (Fig. 122)

GULLIES CUT BY SEASONAL STREAMS in the upper edge of the lowland plains east of Cimarroncito Creek just above Webster Reservoir. (Fig. 123)

It is not hard to visualize such a network extending itself over a plain of any size underlain by uniform rock, given enough time. But the exposed rocks of Philmont are wildly far from uniform. And, as every dacite ridge and sandstone cliff shows, where the rocks are not uniform the drainage becomes concentrated in the softer rocks, which wash out, leaving the harder rocks as ledges. The resulting drainage pattern is not leaflike but reflects the outcrop pattern of the resistant rocks. Thus, little streams run parallel along that part of the mountain front where the steeply upturned edges of dacite porphyry sills and sandstone formations are parallel, and some of the anticlines and synclines in southeastern Philmont are outlined by small streams.

If little streams are so much influenced by rock structure and grow to be big streams, how is it that the perennial main streams and their larger tributaries cut heedlessly in treelike drainage patterns across folds and faults over so much of Philmont and are affected, apparently, only by the largest structure, the arch of the Cimarron Range?

One possibility is that the large streams are older than all the structures but the main arch. Perhaps they began flowing in about their present course before the smaller structures formed and were so well entrenched that they were not diverted by folds and faults that grew slowly across their paths. This is an attractive idea that explains some puzzling stream patterns elsewhere, but it does not fit Philmont very well. If true, it would mean that the streams were well established not just on the plains but in the mountain core in early Tertiary time, for the main time of folding and faulting was well back in the Tertiary Period. By 20 or 30 or 40 million years ago, then, the heads of streams like Ponil, Urraca, and Rayado Creeks would already have reached within a few miles of the crest of the Cimarron Range. Now, of these streams, Ponil Creek, flowing over the Poison Canyon Formation, could not have existed at all, at least not as a carver of landscape, until after Poison Canyon time, 50 or 60 million years ago, as the Poison Canyon was originally deposited over a much larger area than it now covers, probably including southern Philmont; the same, no doubt, applies to all the other streams. The streams were able in a few tens of million years to extend themselves only tens of miles, from the original east limit of the Poison Canyon rocks into the mountain core. In a comparable length of time since the main deformation, they should have been able to extend a few miles farther and deeply notch the mountain crest; but only Cimarron Creek has done so.

Rayado Creek offers direct testimony that the main streams are not older than the mid-Tertiary deformation, but much younger. If there was an early Tertiary Rayado Creek system, it was buried under lava in late Tertiary time, and so were the eroded edges of folds in the sedimentary rocks. Yet in the few million years since the lava flowed, Rayado Creek has been able to establish a drainage system just as complex as that of its neighbors, Urraca and Cimarroncito Creeks, and to dig in just as deeply. The conclusion is hard to excape that the main streams of Philmont, except possibly Cimarron Creek, are no older than late Tertiary and are a great deal younger than the folds they cross.

Rayado Creek also shows how streams can turn the trick of avoiding control by structures older than they are. Rayado Creek clearly started its leaflike drainage pattern when it was running on basalt that dipped gently eastward. This pattern was so deeply grooved that it was preserved after the stream cut through the basalt, even after the basalt was stripped entirely away from the plains, and the creek now runs unconcernedly across prebasalt structures. The leaflike drainage of Rayado Creek is therefore inherited from a time when the creek ran on uniform rocks. To the stream, the folds and faults beneath the prebasalt unconformity *are* younger. On the other hand, the Rayado stream system has been much affected by faults younger than the basalt, as the zigzag courses of lower Agua Fria Creek and of part of Rayado Creek itself attest.

The drainage pattern farther north can be explained in a similar way. The basalt cap seems never to have extended much farther north, but other unfolded, fairly uniform rocks once did, as our discussion of "Missing Layers" brought out. The present oakleaf drainage pattern seems to have been first imprinted in late Tertiary time on thick unresistant sands and gravels that covered most, perhaps all, of Philmont. Once set, the large streams held their courses across the structures that were revealed as the unresistant blanket of loose sediments was stripped away. Only the paths of young tributaries that started after the folds and faults were exposed are controlled by these structures.

The general stream pattern at Philmont is not much influenced by the rocks that the streams are now running across, but each stream is. Its valley and channel respond strongly to the kind of rock the stream crosses, as we shall see in considering each landscape element.

The special history of Cimarron Creek

Cimarron Creek is different from the other creeks and must have had a different history. The other creeks are still chewing away at the east side of the Cimarron Range, but Cimarron Creek has cut clear through the range and has lowered its bed so much that it falls only about 70 feet per mile in crossing Philmont; nearby Cimarroncito Creek, in comparison, falls something like 250 feet per mile across Philmont.

How Cimarron Creek has been able to scoop its canyon so much deeper than other Philmont streams and why it is the master stream of the area seem plain: Cimarron Creek has so much more water to work with. The headwaters of the other creeks drain only a few square miles, but the headwaters of Cimarron Creek drain all of Moreno Valley—300 square miles of low country between the Cimarron Range and the Sangre de Cristo Mountains (fig. 124).

But how did Cimarron Creek manage to capture the waters of Moreno Valley? Where did the streams of Moreno Valley go before Cimarron Creek cut through the range? Or has the Valley been scooped out entirely since late Tertiary time? From what we have learned at Philmont alone, we cannot tell. Others have studied Moreno Valley briefly, however, and have sketched a remarkable story, that makes sense though many details are obscure.

In middle Tertiary time, Moreno Valley did not exist (fig. 124*A*). Instead, a vast blanket of Poison Canyon and younger streamlaid rocks stretched far to the east from the flanks of the Sangre de Cristo Mountains. Later, the Cimarron Range began to rise, and Moreno Valley formed where the land sank between two steep north-south faults (fig. 124*B*). Streams that had flowed far eastward from the Sangre de Cristo Mountains were blocked by the new range but found outlets at the south end of the valley. They began stripping the Tertiary gravel off valley walls and from the valley floor. Then, near the end of the Tertiary, the southern exit too was blocked, by floods of lava (fig. 124*C*). Trapped, the streams became sluggish, and the valley became a swamp or lake that began to fill with sediment.

Eventually, in early Quaternary time, Cimarron Creek, cutting steadily westward, breached the range. Why Cimarron rather than some other Philmont creek was the first to cut through the Range crest is not known. A fair guess is that Cimarron Creek was already the master stream during late Tertiary erosion, and it is shown this way in figure 124*B*; but this only pushes the question back in time. Perhaps the range was most easily breached here because it was broken by east-west faults; perhaps, too, a creek working eastward from about the site of Eagle Nest Dam helped to breach it. Before long the head of Cimarron Creek became the lowest place in Moreno Valley, for only its tributaries had much fall and could do much cutting. Soon all the streams in the valley became tributaries of the Cimarron. The waters that had once flowed east, and then south, again flowed east.

The now faster running tributaries in Moreno Valley began to dissect and remove the lake and swamp deposits and the bedrocks as well. By the time the first Indians came to Moreno Valley, an organized network of streams joined near what is now Eagle Nest and poured eastward into Cimarron Canyon.

Hundreds of years later, early in this century, European men, needing water for irrigation, mining, and recreation, built a dam across the upper canyon; and Eagle Nest Lake came into being (124*D*).

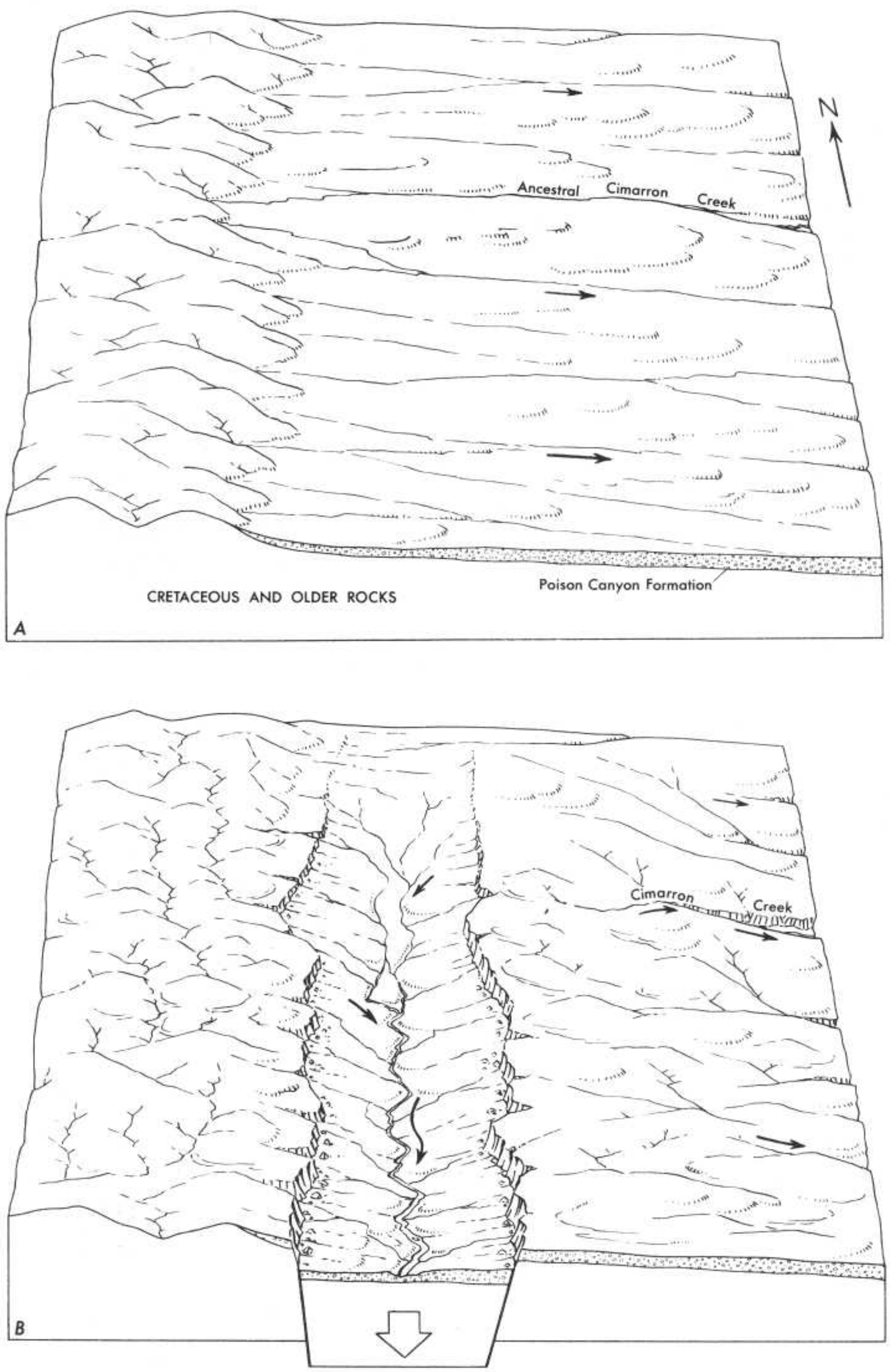
The high benchlands

Now let us consider the origin of the high benchlands, certainly the most widespread kind of landform at Philmont and perhaps the easiest to understand. Although they look much alike from afar, the northern benchlands are very different from the southern and will be discussed separately.

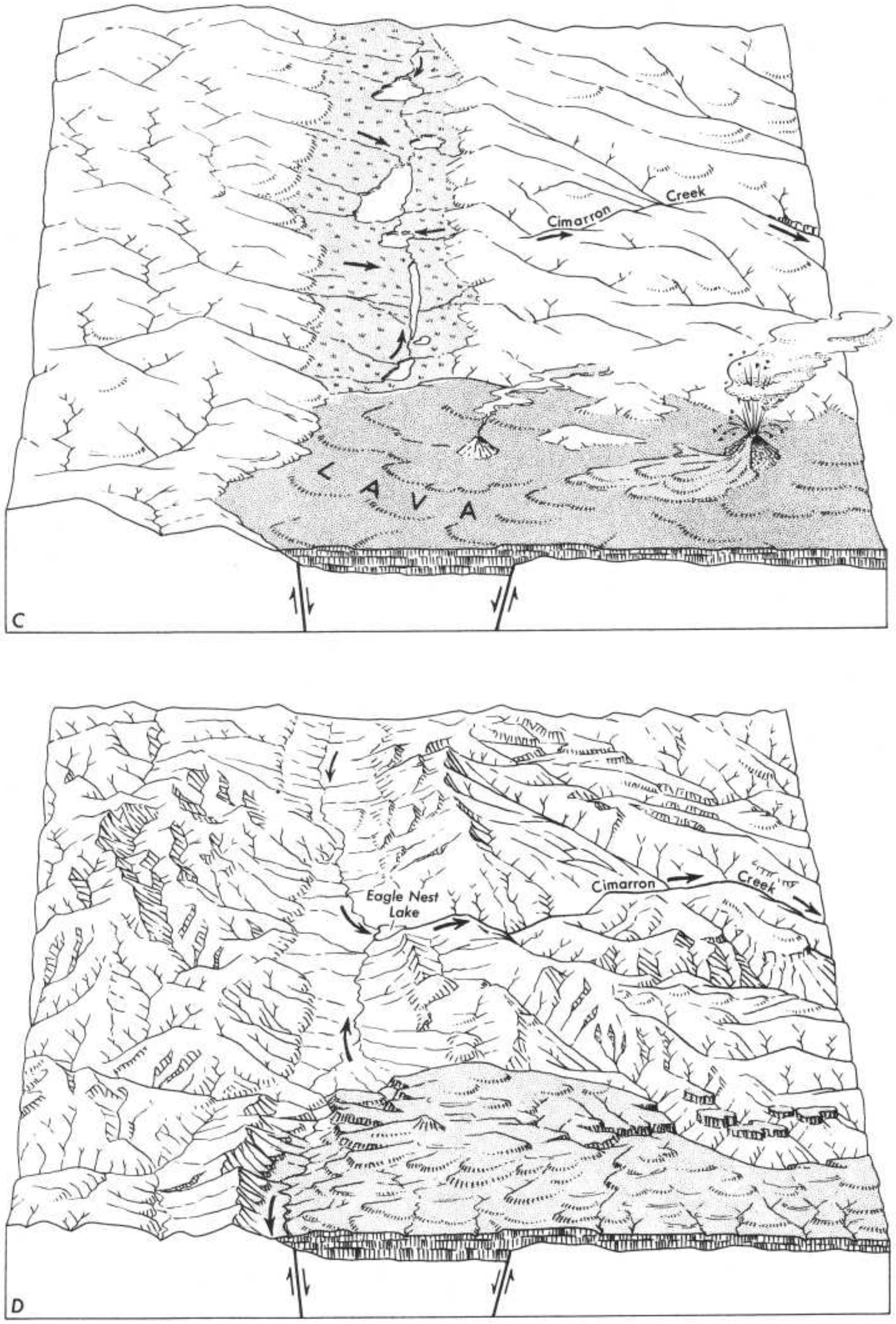
The northern benchlands

Each of the benches north of Cimarron Creek is topped by a layer of very hard sandstone or conglomerate, except for Wilson Mesa, which is topped by a sill of dacite porphyry. At the base of each bench is a thick soft shaly bed, usually concealed by brush or by slide rock. The shale, made of small soft particles that separate easily, has been rapidly excavated, so that a sandstone bench is left below; and the sandstone or dacite layer above is undercut. With its support gone, the hard rock has slabbed off along joints, making the steep bench fronts.

Very soon, the steep bench fronts would disappear, buried in their own rubble, if tremendous volumes of sandstone and shale were not constantly being removed from the scene. We already know one way this might be done: by the alternate sidecutting and downcutting of streams. Is this a workable explanation? To test it, we cannot actually watch a stream cut a bench, but we can do nearly as well by studying gullies of different lengths and depths in a benchland stream canyon.



HOW CIMARRON CREEK CAPTURED THE WATERS OF MORENO VALLEY. A, In middle Tertiary time, Moreno Valley did not exist. Streams flowed east over a blanket of Poison Canyon and older bedded rocks. B, Later, Moreno Valley was created by sinking along north-south faults as the Cimarron Range was rising. Streams that formerly crossed the site of the valley were blocked by the rising Cimarron Range and turned south.

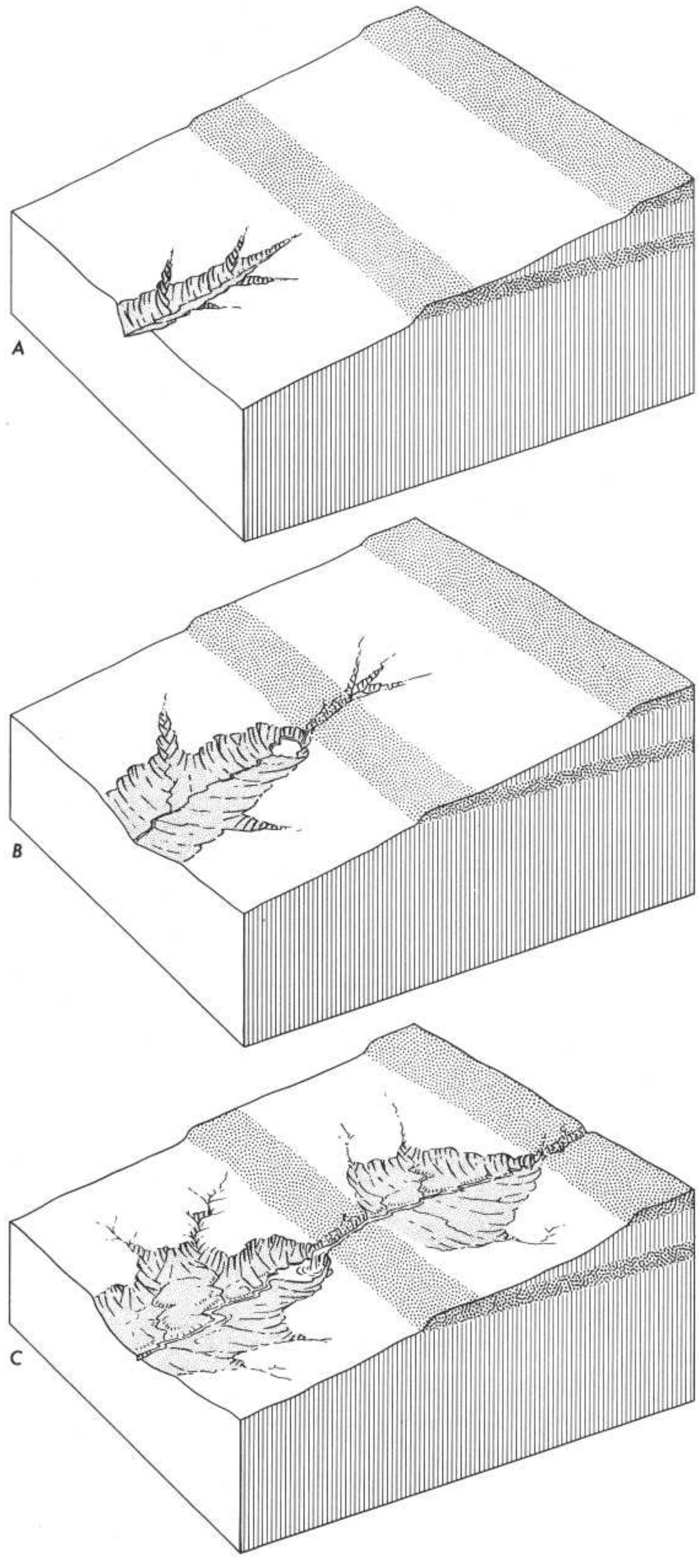


C, Near the end of Tertiary time, the southern outlet was blocked by outpourings of lava. The trapped streams became sluggish, and the valley became a swamp or lake, slowly filling with sediment. But streams from the east, especially Cimarron Creek, were slowly working their way into the Cimarron Rqnge. D, Eventually, Cimarron Creek breached the range and captured the waters of the valley, allowing them once again to flow east. Recently, the outlet was dammed to make Eagle Nest Lake. (Fig. 124)

Start with a smooth canyon wall, such as a new roadcut. Exposed are the edges of alternating beds, each a few feet thick, of shale and sandstone, starting with shale at the base (fig. 125). Beginning in the soft shale, a new stream works rapidly and soon cuts a wide notch (fig. 125*A*). As the stream gets longer and climbs up the canyon wall, it reaches the sandstone above the shale. In the harder, better cemented rock, it cannot cut as rapidly, so it makes a narrow notch that has a much steeper slope than that in the shale (fig. 125*B*). As the growing stream, now carrying particles of hard sand, flows over the shale, it cuts even faster than before at the upstream edge of the shale and soon has scooped the shale out, except where it is protected by the sandstone, and a small waterfall forms (fig. 125*C*). Still growing, the gully meets another shaly bed in which the fledgling stream can again cut rapidly. The edge of the succeeding hard sandstone bed slows the flow so that the stream spreads out and cuts sideways in the shale as well as back.

In this way the stream lengthens its valley unevenly—cutting steeper narrower stretches across harder beds and flatter broader stretches across softer beds. Where the stream flows over the edge of hard layers, it makes little rapids or waterfalls; but across the shale it flows more quietly. At the bottom of its fall, where it is flowing fastest, the stream cuts fastest too, so that downcutting is greatest at the upstream edge of the shale outcrop and slowest at the downstream edge. Streams, then, can cut wide benches in nearly flat beds by stripping soft rock like shale off hard rock like sandstone.

The beds of the large streams also steepen across sandstone and flatten across shale. This is not



HOW STREAMS GROW IN THE NORTHERN BENCHLANDS. A, Gully starting in soft shale. B, Stream, growing longer, begins cutting in hard sandstone. C, Valley becomes steplike—wide and nearly flat in shale; narrow and steep in sandstone. (Fig. 125) so obvious as on small streams, because the large streams, during floods, have dumped gravel in their flatter stretches, smoothing out and concealing changes of slope in the bedrock floor.

Ponil Creek and its tributaries surely have cut their own valleys. In doing so they have left gravel and sand on the valley floor and on the terraces—former valley floors—that wind along on both sides of each stream. But did these streams also cut the broad benches that now rise above them? If they did, the evidence is well hidden. Except next to flood plains, there is no sign that organized streams have ever been at work on the broad benches, for there are no abandoned stream channels and none of the kinds of deposits that streams make. In fact, there is little loose rock of any kind except for angular chunks of sandstone and conglomerate that have fallen from the cliff face and are nestled in little piles at its base.

By watching what happens during a summer storm or a heavy spring thaw, we see how the cutting and moving are done. Sheets of water, muddied by particles of shale, quickly collect at the base of the benches and sweep across them, picking up sand and pebble-size chunks and moving them a little toward the low edge of the bench. Remember that the benches, though they seem to be flat, actually have slopes of several degrees, or several hundred feet to the mile. This is greater than the slope of the bed of either Cimarron or Ponil Creek and is in the same class as the average slopes of Rayado, Cimarroncito, and Urraca Creeks, which are quite capable of moving pebbles.

Often, the water in the sheet disappears by sinking into the ground before it can flow over the edge of the bench; but in storm after storm the rock fragments move ever closer to the cliff edge, eventually falling over and then rolling or creeping to the next bench, to go through the sheetflood procedure again, and finally to reach the stream valleys. So, in a rainy spring, do autumn leaves on a sloping lawn move in a sheet toward the street, until they reach the stream channel of the gutter and are swept away. Rock fragments seem to break off the ledges of northern Philmont at such a slow rate and in such small sizes, and sheet floods are so many and so strong, that the benches are kept nearly free of debris, and their rocky fronts remain steep as they retreat.

The number and height of steps that form in this way depend entirely on the number and thickness of hard and soft layers. Because benches like these are controlled by the bedding and structure of the rocks, they are called structural benches.

We decide, then, that the northern benchlands are carved in gently dipping beds of varying hardness mainly by gravity alone, combined with seasonal sheet floods. The big job of streams has been to haul away the debris, though the streams have surely deepened and widened their own valleys.

As they climb westward, the benches change a good deal in detail. Lower down, in eastern Philmont, bench edges are sharp and clear, as figures 41 and 48*A* show. Because rainfall is sparse, there is little soil and vegetation to slow erosion and to round corners of the benches by chemical decay. Higher, where more abundant rain and snow support open forest (see figs. 7, 9), the sharp edges of the benches are rounded, and the bench fronts are less steep. Still higher, where the forest thins out, the bench edges are also rounded, even though the rocks are bare and there is little chemical decay. (See fig. 76.) Above timberline the temperature goes below freezing almost every night, and the rocks break up by frost action faster than sheetfloods or wind can remove the pieces; so the benches are swathed with sharp-edged rock chips and blocks.

Deer Lake Mesa: Hollowed by the wind?

The top of Deer Lake Mesa (fig. 3) seems not to have formed in the same way as the bench tops north of Cimarron Creek. It is capped by the same rocks that cap the other benches but, unlike them, does not slope smoothly toward the nearest large stream. Instead, Deer Lake Mesa slopes gently inward to form two shallow undrained depressions: Devils Wash Basin, an intermittent lake, and Deer Lake, which is permanent. These basins were certainly not made by running water, either in sheets or in organized streams. Running water does not make depressions but destroys them, either by filling or cutting. Earlier, we thought these depressions might reflect synclines. Are they, then, simply the direct result of downfolding? Possibly, but this would mean recent folding, which is unknown elsewhere at Philmont. More likely, the folds, if any, were made in late Tertiary time when all the other folds in the Poison Canyon Formation were made. Since then, most of the Poison Canyon has been removed (only about 500 feet of it is preserved on the mesa), and not wholly by running water.

If the depressions were not hollowed by streams or bent down by recent folding, perhaps they were made by wind, one of the very few surface agents that can move particles uphill and thus leave a depression. Strong winds, sweeping off the main range of the Sangre de Cristo Mountains and channeled by Cimarron Canyon, may have scoured out fine-grained beds that were once in the cores of the basins. Today, a thin but stubborn cover of soil and vegetation prevents much wind erosion around Philmont. If wind was responsible, it must have done the job when the climate was distinctly drier even than it is today and when the mesa surface was bare rock. Many wind-scoured depressions are forming today in the world's deserts.

The southern benchlands, their meadows and lakes

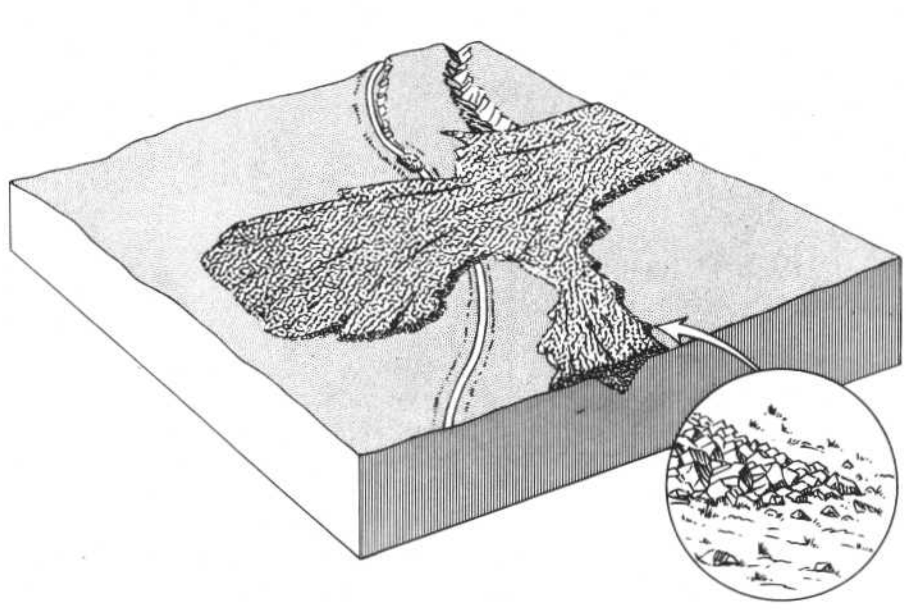
The southern benchlands are like the northern ones in some ways but unlike them in others. They have steep sides and are nearly free of stream deposits, but their tops are rolling rather than smooth, have much more soil and vegetation, and are dotted with marshy meadows and lakes (figs. 12, 20*B*, 20*C*); also, their streams are fewer and smaller. These differences reflect differences in both rocks and structure; the southern benchlands are in slightly tilted basalt rather than in gently folded sedimentary rocks.

Because of the way it forms, basalt lava can build benchlands without the help of water or wind merely by piling up on the surface after filling in the low places. The hot lava, though a liquid, is very much thicker than water and has a freezing temperature about 2000° F. above that of water, so it flows slowly and congeals quickly. No eye-witness accounts, or even legends, tell of lava flowing at Philmont; but eruptions of basalt are common affairs in many places, especially on the borders of the Pacific Ocean and on Pacific Islands, so we can be sure of what happens when lava makes benches.

Soon after a tongue of lava, white-hot, pours out of a crater vent or a fissure, its top, bottom, and sides freeze into a black crust. Insulated by this crust, the lava within stays molten and creeps downslope like a moving stone wall or a tractor, flowing over a floor of its own crust, here pushing blocks and plates of broken crust before it, there breaking through and gushing over the crust, only to freeze at once and make new crust. Before long, a big flow fills in the low places that guided it at first. It becomes a sticky river, flowing on a self-made bed and between self-made banks, perhaps many feet above the ground it started on (fig. 126). When it finally stops, because no more lava is supplied from below, it has formed a steep-sided bench or mesa and has a top that is rough and irregular and is pitted by many depressions that can hold rainwater. The edges too are a jumble of broken blocks; the familiar pencil-shape joint blocks on old flows are the sides of cooling columns from well inside the flow that have been exposed by erosion of the original rough edge. Later a flow may be buried by a larger flow, but successively smaller outflows may build a series of bench steps.

The single lava flow of which Rayado Peak, Fowler Mesa, and Urraca Mesa are the dissected remnants is such a constructional bench (fig. 45). The highest bench of the several that make Ocaté Mesa was also built rather than cut. The lower benches may have been also, but the evidence needed to be sure of this is hidden under soil, vegetation, and slide rock; possibly, some or all of these benches have been eroded from alternate resistant and unresistant layers of volcanic rocks and thus are structural benches like the northern ones.

Even the first lava flows were poured out on a smooth, gently dipping surface, for their floors are parallel to their smooth and gently dipping tops; and no lava seems ever to have flowed into any canyons, ancient or modern. Here and there, a little typical stream



RIVER OF LAVA freezes to make a bench. The inset is a close-up of the jumbled blocks of broken crust at the edge of a new lava flow. (Fig. 126) gravel is found between the lava and the underlying shale bedrock and is good evidence that the prelava plain was cut by streams—the same streams, no doubt, that stripped the Tertiary rocks from southern Philmont. The lava flows, therefore, not only made new benches but protected an old one.

The southern benchlands have more soil and vegetation partly because the basalt has low dips and many original depressions, so that rainwater stays longer and does more in the way of chemical decay than it does on the northern benches, but mostly, perhaps, because of the nature of basalt. Basalt is rich in magnesium, iron, calcium, and other metals needed to make fertile soil, and the glass of which it is mostly composed quickly weathers to clay if there is plenty of moisture. The small part of the Ocaté Mesa included in Philmont is high, fairly rainy country; so its basalt, which is probably a few million years old, is deeply weathered and supports much vegetation. (Just to the south, basalt flows extend several miles out onto the dry plains; and there the basalt, despite its age, is only slightly weathered and supports only a little grass.)

How is it that so many marshy meadows and lakes exist on the Ocaté Mesa although streams have been able to drain nearly all such places elsewhere on Philmont? It is partly a matter of time, for before any streams had started to run in the basalt, streams in northern Philmont were well organized and working away. It is partly a matter of surface slope also, for the streams in northern Philmont have always had steeper slopes to flow down than those in the basalt; therefore the northern streams could flow faster, cut more, and grow faster.

It is also a matter of the nature of the basalt itself. The new basalt was honeycombed with cooling cracks. Instead of running off the surface in sheets and streams, rainfall and melt water sank into these cracks and disappeared into the ground, so that streams formed slowly. And because the basalt weathered so easily, it soon grew a protective blanket of soil and plants that took over the job of slowing stream growth.

The lowland plains

The lowland plains are carved into giant steps like the benchlands that flank them (fig. 8). The steps are still forming on both benchlands and plains: bench fronts are slowly retreating, and the lowest steps—the flood plains of present streams—are being widened, lengthened, and coated with more and more gravel and sand. Plainly, the benches in both kinds of landscape have been growing side by side for a long time. Nevertheless, they are very different and cannot be accounted for in the same way. The steps on the plains are cut almost wholly in soft shale, so they are not due to differing resistance of bedded rocks. They cut smoothly across large folds that bring up not only shale but hard limestone, so they are not controlled by the dip of the bedded rocks. And they are covered by a thin but nearly continuous blanket of somewhat rounded gravel and sand of the sort deposited by organized streams, so they apparently are not the product of gravity fall and sheetfloods. They seem, then, to be stream terraces.

The origin of the plains comes down to two questions: what streams planed off the shale and veneered it with gravel and sand? Why, in fairly uniform material, did downcutting alternate with sidecutting to make steps? We have not done enough work to be sure of answers, but we can at least discuss some of the possibilities.

At first glance, the nature of the responsible streams seems obvious. Surely the same east-flowing streams that exist today cut and almost simultaneously capped the benches by wandering back and forth over the soft shale after leaving their canyons in the hard mountain rocks. The eastward slope of the terraces seems to fit this idea. But it is not that easy. We have already reasoned that the streams have a leaflike drainage pattern because they are a carbon copy of drainage that started on a surface of uniform unfolded rocks that are now washed away. If the mountain streams had slowed down enough to wander much from their early paths, they would have been influenced by the folded structures, especially where the folds bring up hard limestone; and the oak-leaf drainage would not have lasted very long—yet it has persisted long enough for many cubic miles of shale to wash slowly away in the cutting of the plains, and long enough for several cubic miles of sand and gravel to be dumped on the cut surfaces. The eastward slope, which is very steep for meandering streams on soft rocks, is very likely the result of Quaternary uplift of the Cimarron Range.

An alternative to east-flowing streams is the Canadian River, which flows south parallel to the mountain crest and is the master stream of a region much larger than Philmont (fig. 1). Suppose that the Canadian River, in early Quaternary time, flowed on a flood plain a mile or two wide close to the mountain front, and suppose also that the ancestors of the present streams emptied into it there. As the mountains rose on the west, the eastward slope

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caused the Canadian River and its flood plain to shift eastward; and the mouths of the tributaries also migrated eastward, across loose gravel of the earlier flood plain. If this is true, our ideas on the origin of leaflike drainage east of the mountains will need to be modified: the drainage has been inherited directly from a pattern formed on Quaternary rocks rather than on Tertiary ones.

This idea also can be used to explain the steps. Suppose that the Quaternary rise of the range was not smooth but was in a series of jerky steps, having long pauses between. Each pause would produce wide gravel-clad flood plains. Each rise, by increasing the slope of the tributaries as well as by shifting the main river eastward, would cause the streams to dissect their flood plains, leaving terraces.

This sounds fine, and it may even be true; but there are other ways besides steplike uplift to make streams alternate between downcutting and sidecutting, ways that cannot be disregarded in our state of ignorance. Consider a few.

Suppose, for example, that a steep fault having many feet of vertical movement broke across the Canadian River not far downstream from Philmont. If the downstream side rose, the river might be dammed to form a lake. As long as the lake existed, the speed of the stream and its tributaries would be greatly reduced; and the streams would start cutting sideways, drop their loads, and produce a gravel-topped flood plain. When the lake was destroyed, by filling or by breaching, the main river would resume speed and begin cutting down; the tributaries would do the same, leaving the old flood plain as a terrace. A lava flow across the river could have the same effect.

If, however, the downstream side of our hypothetical fault dropped, the result would be a waterfall or a rapid. The fall of the river upstream would increase, and general downcutting by both river and tributaries might follow, until the waterfall had been reduced to a normal slope for the river. If downstream faults or lava flows are responsible for the terracing of the plains, they have so far escaped detection.

Persistent changes in climate, either to wetter or drier, can also cause streams to cut and build terraces. Suppose, after a single broad flood plain was built in a dry climate, that the rainfall increased markedly. More and higher floods would lead at first to more erosion, and the flood plain might be dissected, leaving a terrace. But heavy rainfall continued for centuries would lead to deep weathering, thick soil, and dense plant cover. In turn, soil and plants would retard erosion and lead to another episode of side cutting.

Now suppose that the building of a single broad flood plain in a rather damp climate is followed by long drought. At first stream flow would be reduced and deposition increased, merely extending the flood plain or thickening its gravel cover. Soon, however, the plant cover would thin, and erosion would become easier. As the use of water by plants declined, the amount of water in the streams would actually increase, and the flood plain would be dissected to become a terrace. In a small way this is now happening at Philmont, which, like the rest of the Southwest, is in a dry period that started about 1850; many streams have cut down several feet, and hosts of new gullies have scarred the plains. (See fig. 123.)

Long wet periods alternated with long dry ones in earlier Quaternary time as vast ice sheets from centers in Canada advanced and retreated on the Great Plains. These climatic changes may have been responsible for some or all of the terrace steps, after the highest plains surface was cut.

It is even conceivable that, despite the evidence of the stream gravel cover, the higher benches of the plains were not cut by streams at all. Perhaps, as the range rose, shale between stream canyons was stripped by sheetfloods and slow earth flow, just as on the northern benches, and wandering streams dumped gravel on them later.

Landscape puzzles can be as difficult and intriguing as structural puzzles.

Waterfalls and mountain meadows

In the mountain core, stream valleys flatten and widen out in the metamorphic rocks upstream from hard-rock ledges of sandstone and dacite porphyry; stream channels are shallow and broad, and the streams wander sluggishly across the valley floor. Bonito Creek, the largest stream that heads in metamorphic rocks and crosses the mountain front, has cut down so far in the metamorphic rocks near the front that its valley has become a long meadow (fig. 127). But the stream valleys narrow and steepen abruptly where they cross the hard-rock ledges. Stream channels become narrow and deep, and the water, swift; rapids form where the channel crosses narrow ledges, and waterfalls form where it crosses wide ones. This suggests that the metamorphic rocks are more easily eroded by streams than are the sandstone or dacite porphyry. In turn this seems to tell the same story that the benchlands told: the waterfalls at the mountain front and the ledges that extend beyond the waterfalls may be structural benches cut on the bias.

The evidence of geologically late uplifts in the region, however, leads to a different possible explanation of the mountain meadows along middle Bonito Creek. Perhaps Bonito Creek once reached a stage at which it flowed through an ever widening valley across metamorphic, sedimentary, and igneous rocks alike to its junction with the Canadian River. Then a pulse of mountain uplift started a wave of downcutting that has worked its way headward only as far as the present mountain front, so that the meadows are the remnants of an older, interrupted episode of valley widening.

The future of waterfalls is interesting to consider. The waterfall best known to Americans is Niagara Falls, which is in flat rocks; everyone has heard or read that it is retreating upstream, and it is natural to assume that all falls do the same. Waterfalls in flat-lying rocks *do* retreat upstream. But in rocks that dip, the matter is more complicated. If the dip is upstream, or is downstream but at an angle lower than the slope of the stream channel, falls retreat as in flat beds. If the dip is downstream, though, as it is along nearly all the mountain front, the falls will advance. Falls across vertical beds, as on South Fork Urraca Creek, will not migrate at all.

The marshy meadows along lower Agua Fria Creek (fig. 10) at the junction with Rayado Creek look like those on upper Bonito Creek, but they cannot have had the same origin; for there are no hard sandstone or dacite ledges just downstream, and Rayado Creek valley does not have a broad meadow reach near the junction. Agua Fria Creek has been able to cut its bed down faster than other streams in the Rayado Creek system, so that it meanders sluggishly on a marshy flood plain, partly because it is running in crushed rocks along a fault and partly because it drains a much larger area than the other creeks and so has had more water to work with. Agua Fria Creek is reminiscent of Cimarron Creek, which has cut its bed much lower than neighboring streams for apparently the same reasons.

MOUNTAIN MEADOWS where Bonito Creek runs on metamorphic rocks, upstream from hardrock ledges at the mountain front. (Fig. 127)

The rugged mountain country

The mountains begin where hard layered rocks—Dakota Sandstone and dacite porphyry sills—crop out and dip 25° or more. The most rugged mountains are not deep in the range but at the very front, where these same moderately to steeply dipping hard layers alternate with soft ones of shaly rocks. The highest part of the mountain country, Touch-Me-Not Mountain, is held up mostly by thick sills of hard dacite porphyry that have moderate to low dips near the crest of the Cimarron Range anticline. Even the shale between the sills is a fairly hard rock, because it has been baked and hardened by the intrusions. It seems clear that the mountains exist because their hard rocks have been arched up, faster than streams could strip them away, in a great surge in middle Tertiary time and in many lesser pulses since.

At first glance, the Precambrian metamorphic and igneous rocks in the mountain core do not seem very resistant to erosion, judging by the general roundness of the terrain, the scarcity of outcrops, and the many small closely-spaced streams. All this surely means that weather and water easily attack these rocks at the surface through the countless openings provided by cleavage, joints, and other fractures. But appearances are often deceiving, and a soft glove often covers a hard fist. Precambrian crystalline rocks form the core not only of the Cimarron Range but of many ranges throughout the Rocky Mountains, some of them far loftier and more rugged than the Cimarron Range. They must, therefore, be among the most resistant of rocks to erosion in Rocky Mountain climates and at Rocky Mountain altitudes. Evidently, the fractures that lead to easy breakdown are open only near the surface. Farther down, most of the cracks are too tight for ground water to move and work in them, and these rocks, unlike many sedimentary rocks, have none of the connected pores between grains that allow fluids to circulate. The mantle of soil, at lower altitudes, and rubble, at higher altitudes, that forms so readily on these crystalline rocks thus simply serves to protect them.

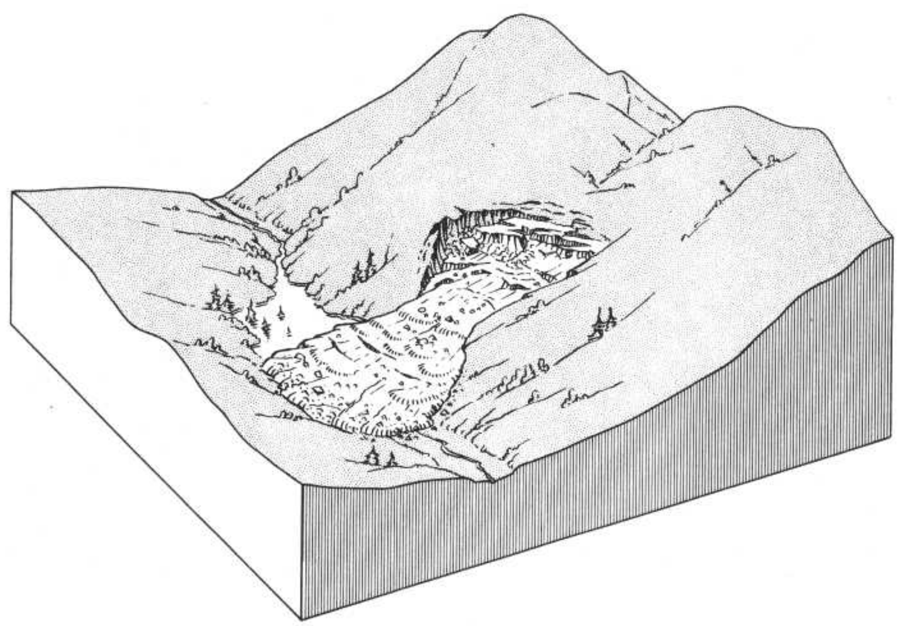
Hummocky hillsides: Fossil landslides

Something like 50 square miles of Philmont has rough, hummocky hill slopes that resemble great landslides. (But not all the area shown as landslides on the geologic map is really underlain by slides; included are some areas of rockfall and hillwash.) These are slides of the past, for they are overgrown with soil and trees. Why did they form, and when?

No landslides have been seen in motion at Philmont, but there is little doubt about what happens in most slides, for small ones are familiar events: on a steep hillside after heavy rains, or in a streambank after a flood, a scoop-shaped mass of soil and rock suddenly slides downhill as a unit (fig. 128). Its front is a wall of jumbled rock and soil; its surface is broken by concentric cracks and humps and is dimpled with depressions in which water may collect. Most landslides are small—a few tons of rock slide a few feet. In many mountainous regions, however, very large landslides often endanger or destroy lives and property. Some are shaken down by earthquakes caused by faulting or volcanic activity. Most landslides, however, seem to happen when fractured rocks or soils exposed on steep surfaces are heavily wetted for a long time. The water increases the weight of the rock and lubricates the fractures, so that the rock can no longer support its own weight and starts to slide.

Most of these conditions are met over a large part of Philmont, where there are many thick exposures of black shale that are steep because they are protected by hard caprock—dacite porphyry or sandstone (fig. 3) or basalt (fig. 45). The mere fact that black shale is soft and slippery is not enough. If it were, much of the benchlands and all the plains would be vast landslide jumbles, for black shale is at the surface or not far below. To slide, the shale evidently must be exposed so that surface water can soak in it, and it must have steep slopes so that the rock is already near the sliding point.

One condition that favors landsliding, however, is not met at Philmont. In the present semiarid climate, there is not enough moisture to keep the shale wetted for very long. This is why the slides are not very active now. They are relics of a wetter past. When was this? It was after the higher graveled plains were built, for the slides extend far lower in some places, and in others, such as around Urraca Mesa, they ride out over the plains. It was before the flood plains of the present streams were built, for several of these are cut into slides. And it was not all at once, to judge by differences in the amount of dissection of the slides. The slide



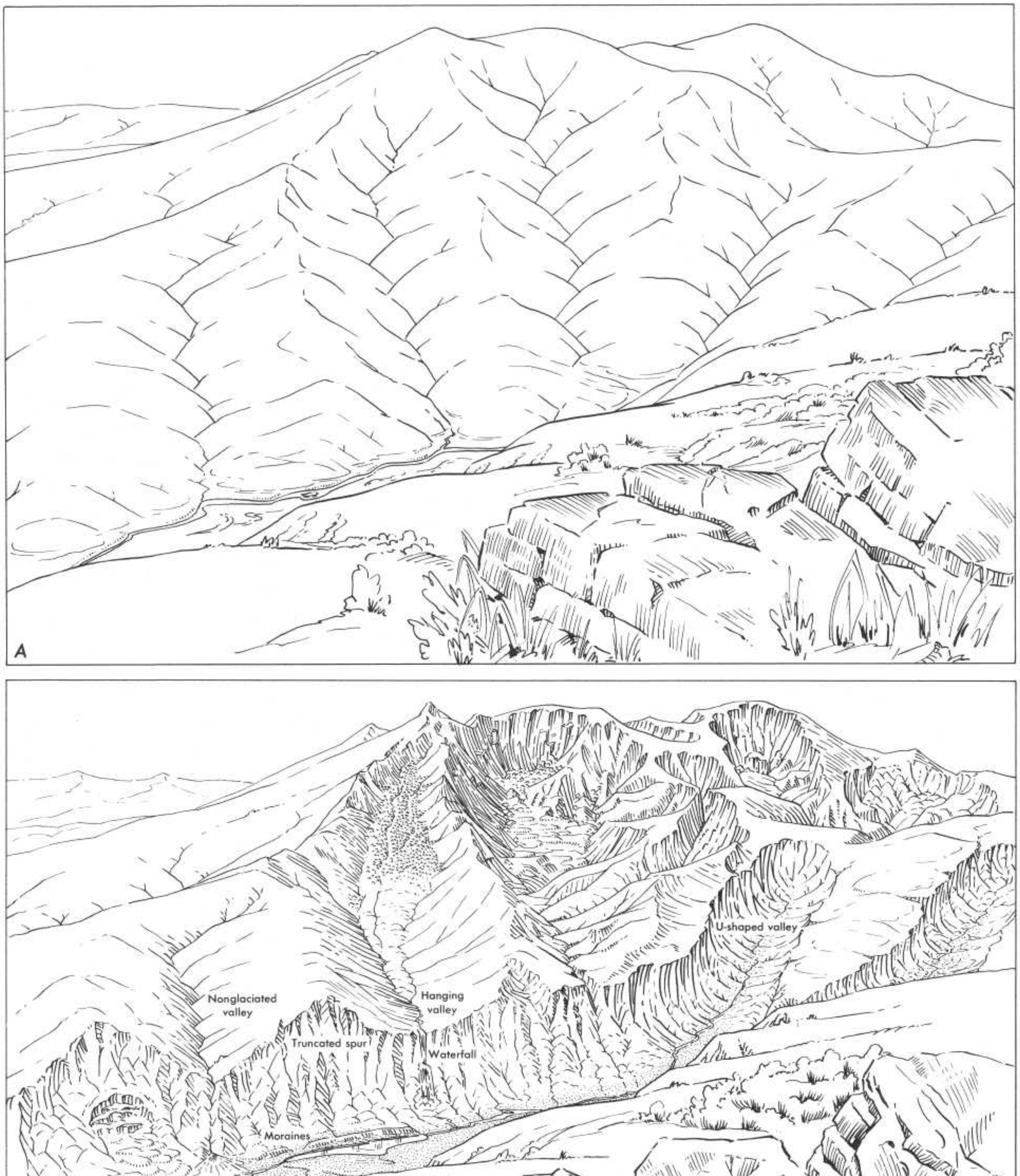
TYPICAL LANDSLIDE. A lake has formed upstream from the landslide. (Fig. 128)

CRATER LAKE. Not a crater but a water-filled depression in an undissected landslide. (Fig. 129)

areas in southern Philmont, which are beneath basalt caps, seem distinctly younger than those farther north, as they have fewer streams and many more undrained depressions. Crater Lake is a water-filled depression in an undissected landslide and is not in a crater at all (fig. 129).

The landslides, then, were moving during earlier parts of Quaternary time when the climate was much wetter. Probably this was when ice sheets were advancing from Canada over the Great Plains far to the north and east and when valley glaciers nestled between the high peaks of the Sangre de Cristo Mountains nearby to the west and north. Although there seem to have been two main times for landsliding, it does not follow that the slides all formed in two great rushes. More likely, individual slides a few hundred feet wide oozed down at the rate of a few feet a day or month with long pauses between, so that the large slide areas were growing for thousands of years. Piecemeal formation like this may not be romantic, but it is the way things usually happen in nature.

Not always with landslides, though. Some huge and catastrophically sudden ones are known. One of the largest and most destructive in modern times roared through the Swiss village of Elm in 1881. Late one September afternoon, after heavy rains, a steep quarry face cut into a slate cliff 2,000 feet high suddenly gave way, and 13 million cubic yards of rock fell 1,500 feet in less than a minute, spreading rubble 30 to 60 feet deep over a third of a square mile, destroying houses and everything else in its path, and killing 115 people. Blocks as large as 20 feet across travelled almost a mile. The average speed of the slide front was 93 miles an hour!



VALLEY SCULPTURE by a mountain glacier. A, Before glaciation. B, After the glacier melts. (Fig. 130)

Glaciers?

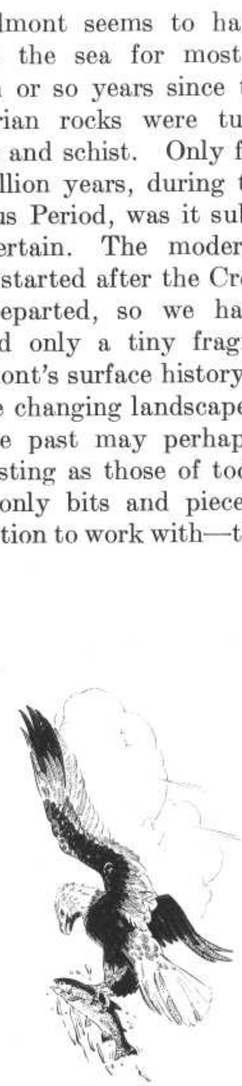
The landslides are among the few mementos of the Ice Age at Philmont. There are no landforms and no deposits to suggest that glaciers ever grew on the slopes of the Cimarron Range. As there are still many mountain glaciers in the world, a great deal is known about their habits, and this statement can be made with confidence.

Mountain glaciers form at the heads of streams, where they scoop out bowl-shaped depressions (fig. 130). If enough ice forms so that it overflows and moves downstream, the ice, which is not as fluid as the running water it has displaced and is a much better scouring tool, deepens and widens the originally V-shaped valley to a U shape and straightens it out by grinding off projecting rock spurs between tributaries. The tributary valleys, which are too small to support glaciers, are not deepened along with the main valley; instead, they hang high in the air, and, when the glacier retreats, their streams drop to the main valley in waterfalls. The glacier scrapes and plucks innumerable large and small chunks of rock off the valley walls and floor and carries these pieces to the glacier front, along with rocks that tumble down the valley side onto the glacier. The piles and fields of glacier-borne rock, called moraines, are left after the glacier itself melts and disappears. Other spoor left by glaciers in valleys are two kinds of lakes: rock-rimmed tarns near valley heads, where the ice has scooped out basins, and finger lakes dammed by moraines. None of these signs of glaciers appear in even the highest parts of Philmont.

Landscapes of the past

Philmont seems to have been above the sea for most of the billion or so years since the Precambrian rocks were turned to gneiss and schist. Only for 60 to 70 million years, during the Cretaceous Period, was it submerged for certain. The modern landscape started after the Cretaceous sea departed, so we have considered only a tiny fragment of Philmont's surface history.

The changing landscapes of the remote past may perhaps be as interesting as those of today, but with only bits and pieces of information to work with—the curve of an unconformity seen in a cliff, the direction of thickening or coarsening of one formation, the kinds of plants or animals buried in another—we cannot hope to reconstruct them except in the most general way.



If a landscape begins when an area emerges from the sea and ends when the sea again covers it, only one landscape and a fraction of another have existed for sure in the long history of Philmont. The first began some time before the Sangre de Cristo Formation started to form in the Pennsylvanian Period and ended with the invasion of the Early Cretaceous sea. It may have endured for hundreds of millions of years before the Pennsylvanian, or the unconformity beneath the Sangre de Cristo rocks may be all that is left of an elaborate cavalcade of alternate landscapes and seascapes. About all that can safely be said about how Philmont looked in pre-Cretaceous time is that it was mostly lower land than neighboring regions from the Pennsylvanian through the Jurassic but may often have been a highland before that.

Another way to think of landscapes is simply as surfaces of erosion on land, for landscapes are far more cut than built. Looked at this way, there have been at least half a dozen landscapes at Philmont, as every unconformity records both an erosion surface and its extinction by burial.

RESTLESS MOUNTAINS
RESTLESS PLAINS
The geologic history of Philmont

Bit by bit we have discovered the main events at Philmont during the last 300 million years, and we have collected some helpful hints about happenings in the billion years before that. Where time has been involved, we have usually worked backward. Now let's try to put the main pieces in chronological order. And, to make the story more readable, we will tell it as though we know the answers to many unanswered questions. It should be read, then, with slightly lifted eyebrows.

It will be a lively tale, but almost lifeless: living things will be ignored, except for a few vague remarks about vegetation. Surely organisms of increasing complexity have flourished at Philmont for much more than a billion years, but there is not enough local evidence on which to build a history of life at Philmont.

The first 2 to 3 billion years at Philmont—indeed, almost everywhere on the earth—are still veiled in darkness. The veil lifts briefly a billion or more years ago: layered rocks, at least some of which had been deposited in water, are folded deep within the earth and recrystallized by heat and rock pressure to become gneiss, schist, and quartzite. Some of the downfolded rocks become hot enough to melt partly and to flow upward, intruding the metamorphic rocks, and crystallize to granodiorite; in water-rich parts of the melt, crystals grow large, to become granodiorite pegmatite. The metamorphism, melting, intrusion, and crystallization take millions of years, during which much of the rock cover that supplies the metamorphic pressure is being stripped off by erosion, and the granodiorite is metamorphosed but slightly.

At Philmont the veil descends again for the rest of Precambrian time and for most of Paleozoic time. A good guess is that Philmont is land near the southeast edge of a great island for most of these 700 million years or more. In all that time, streams and other agents of erosion would surely have leveled the highest mountain range several times over; probably, then, the island does not merely sit there but is often uplifted. At other times it may sink or be eroded so low that it collects sediments, but any that collect before Pennsylvanian time are stripped away after uplifts.

By Pennsylvanian time, 300 million years ago, erosion has gone so deep that the same Precambrian rocks we now see are near the surface. Southern Philmont is part of the broad valley of a great east-flowing river and is only a few hundred feet above the sea, which laps gently on low shores not many miles to the east and south. Northern Philmont is rolling hill country. Mountains, which are fairly high but rounded and have deep red soil on the slopes between stream valleys, loom to the west. The climate is warm and damp, perhaps almost tropical, and lush low-growing vegetation abounds. Philmont is far more like present-day northern Georgia than northern New Mexico. A river laden with red-stained gravel, sand, and mud from the mountains wanders sluggishly across the valley floor in southern Philmont, dropping gravel and sand along its channel and carrying fine mud beyond to the sea. In rare floods, the river overflows its banks, leaving layers of mud on the bordering plain. In some stagnant ponds on the flood plains, calcium carbonate settles out of the water and collects as lime mud on the bottom. In other ponds, algae take up the calcium carbonate and turn it into biscuit-shaped pebbles of limestone.

This is Philmont for 80 million years, through the Pennsylvanian and Permian Periods. In southern Philmont, 5,000 feet of stream and pond deposits pile up; and finally even the high country of northern Philmont is buried by gravel and sand, out of which protrude only a few low ridges of gneiss, schist, and granodiorite. As the loose wet sediments age and are buried deeper and deeper, they gradually become the solid rocks we call Sangre de Cristo Formation.

As the Paleozoic Era ends, 230 million years ago, Philmont is part of a vast plain that is near sea level despite the great pile of sediment it has been receiving. It has been sinking about as fast as the sediments have been piling up.

If any sediments are deposited in Early Triassic time, they are soon eroded. Probably, the mountains to the west have been worn so low that they are not supplying much sediment to streams, and there is neither much deposition nor erosion at Philmont.

In Late Triassic time, 200 million years ago, the deeply weathered mountains to the west are again uplifted; streams begin again to deposit red gravel and sand on Philmont, and again limestone mud settles out of overflow ponds. Uplift in the mountains fails to keep pace with erosion, and toward the end of Triassic time the streams are depositing mostly mud and fine sand. These red sediments, which are 400 to 500 feet thick, will eventually harden into the Dockum Group. The basin of which Philmont is now a part continues to sink as sediments thicken, and at the end of the Triassic Period the Philmont plain is still near sea level, and the nearest salt water is only miles away to the east.

Through Late Triassic time the climate remains warm but becomes gradually drier. By 170 million years ago, in Early Jurassic time, the region around Philmont has probably become a coastal desert not unlike the Sahara. Desert winds and rare rainstorms begin sweeping fine sand and clay from the bare and still loose upper part of the Dockum Group; but any deposits they make in Early Jurassic time they soon destroy. In later Jurassic time, however, winds and floods pile up about 50 feet of dunes and layers of nearly pure quartz sand on the desert floor; these are not destroyed but become the Entrada Sandstone. Then the mountains to the west again rise; the climate grows damper, and streams again start dumping red mud and sand on Philmont; and once more limestone starts forming in overflow ponds. By the end of the Jurassic, 135 million years ago, 400 feet of these sediments, which will become the Morrison Formation, has collected.

For at least 150 million years, Philmont has been sinking more often than rising but has stayed a little above the sea. Now, in Early Cretaceous time, it sinks a little faster than streams can build it up, the sea washes over it, and Philmont becomes a tidewater beach. Waves and currents pick up small fragments, mostly of clay and mica, and carry them offshore and dump them in mud banks. The sand remains on the beach, washed and winnowed many times by waves and, in places, piled up into dunes by winds. After 50 feet of beach and dune sands accumulates, the sea advances westward, and so does the line of coastal dunes. Philmont itself is covered by deeper water; the sand is buried by mud carried from the land. Once more the sea retreats; Philmont is again a tidal beach whipped by winds, and another layer of mixed beach and dune sand grows. The two sand layers and the muds between will eventually become the sandstone and shale of the Dakota Sandstone, 100 to 200 feet thick.

Again, Philmont sinks faster than the sediments thicken, and in Late Cretaceous time the sea again advances, this time far to the west, leaving Philmont under shallow salt water for many millions of years, long enough for several thousand feet of offshore deposits to pile up, mostly black clay mud washed off lowlands far to the west. Now and then, clouds of light-colored ash from volcanoes still farther west shower on the water and settle to the sea floor. In quiet waters bypassed by muddy currents, pods and thin layers of lime mud grow. The clayey and ashy mud deposits harden to become the Graneros, Carlile, Niobrara, and Pierre Formations, together more than 3,000 feet thick; widespread lime-mud layers above the Graneros Shale solidify to become the Greenhorn Limestone, about 30 feet thick, and others above the Carlile Shale become the Fort Hays Limestone Member, about 50 feet thick.

Then, 100 million years ago, in very late Cretaceous time, land reappears to the west, and the sea starts retreating eastward. Philmont becomes part of the seashore again and is covered by 100 feet of sand brought by streams from the new land and spread by waves and current along the beach—the Trinidad Sandstone.

The sea now oscillates rapidly across Philmont as the land to the west is worn down to a plain. When the shoreline moves east, Philmont is a maze of coastal swamps and lagoons in which brown mud and masses of partly decayed vegetation gather; when Philmont is in the shore zone, layers of sand pile up. Thus form the yellow and gray sandstone, brown shale, and coal of the Vermejo Formation, more than 150 feet thick.

A bit more than 70 million years ago, just before the end of the Cretaceous Period, the land to the west rises abruptly, and western Philmont rises with it. The sea retreats eastward, never to return. The retreating sea and the new streams that start flowing eastward down the tilted surface strip the Vermejo and Trinidad rocks off western and southern Philmont. Then the streams blanket most of Philmont with gravel as sinking to the east creates the Raton basin and reduces stream gradients.

As late Cretaceous time passes imperceptibly into early Tertiary time, the main range to the west keeps rising fast enough to supply coarse gravel as well as finer debris to east-flowing streams; but continued sinking east of Philmont leads to poor drainage and swampy conditions in northeastern Philmont. Philmont now lies between a rising range on the west and a foundering basin on the east. The mountain streams dump their gravel and coarse sand in western Philmont, and their fine sand and mud in swampy eastern Philmont and beyond. The climate is still warm and wet, and low eastern Philmont is a green jungle, something like the Everglades of Florida. Matted piles of partly decayed vegetation become peat and are buried by mud as the shifting streams overflow. In this way the Poison Canyon Formation grows on the west at the same time as the Raton Formation grows on the east. After especially rapid uplifts on the west, tongues of coarse Poison Canyon rocks reach far out into the basin; when uplift is especially slow, layers of fine-grained Raton rocks reach far west. As early Tertiary time goes by, the climate turns drier, and the Raton basin ceases to be a swamp, after 1,500 feet of Raton Formation has accumulated in northeastern Philmont. But the main range of the Sangre de Cristo Mountains keeps rising and shedding coarse Poison Canyon sediments that finally become more than 2,000 feet thick and bury all of Philmont.

For a while Philmont is again a low rolling plain crossed by a few sluggish streams. It is less than a thousand feet above the sea but is hundreds of miles from the nearest salt water.

Now comes the birth of the Cimarron Range. A gigantic block of Precambrian metamorphic rocks, stretching southeastward from the ancestral Sangre de Cristo Mountains into western Philmont, begins to rise. It arches the sedimentary rocks above it, crumples and in places breaks through those on its sides, and sends waves of folds outward. Magma begins to rise along cracks and faults, especially at the margins of the rising block. The magma creeps between the sedimentary rocks in some places, spreading them apart; in other places it squeezes the soft sediments out. Soon the cover and flanks of the rising arch are laced with sills and dikes of dacite porphyry and andesite. Far out on the flanks a different kind of molten rock is rising up cracks, to freeze into lamprophyre; or perhaps the lamprophyre is intruded somewhat later. Though it is still rather early in Tertiary time, the Cimarron Range has developed the geologic structure it has today. It may, too, be a mountain range like that of today, though uplift may be slow enough for erosion to keep the mountains low. On the rising arch, streams form a radial drainage pattern and begin carrying rock debris to the sea.

For a while the range is simply part of the eastern foothills of the nobler range to the west, but then a series of north-trending faults drop a long tract of country to form ancestral Moreno Valley, which drains to the south. The Cimarron Range becomes, as it still is, a rocky peninsula jutting southeast from the Sangre de Cristo Mountains. Now the streams, deprived of their headwaters and of much of their fall by the creation of Moreno Valley, begin wandering back and forth, dropping their burdens, until Philmont is covered by a thick blanket of sand and gravel. Once again it is a lowland plain probably no more than 2 to 3 thousand feet above sea level; vestiges of this plain may still be preserved as the Park Plateau.

Near the end of the Tertiary, the pace of deformation, and therefore of erosion, quickens. The range starts rising again, and the streams, refreshed, begin stripping off the loose sand and gravel blanket and digging into the solid rocks beneath. In southern Philmont, and beyond to the south and west, volcanoes erupt. Lava fills many shallow valleys and then piles up in broad sheets that spread a little way out on the plains south of Philmont to form the Ocaté Plateau. Lava also dams the southern outlet of Moreno Valley.

Streams in northern Philmont, and those which quickly grow in the volcanic rocks of southern Philmont as volcanic activity wanes, probably empty into an ancestor of the Canadian River that flows southwestward into Philmont near where Cimarron will be, swings westward in a broad arc, and then swings eastward to skirt the base of the lava-capped Gonzalitos Mesa.

As the range rises several thousand feet, a little at a time, the plains to the east rise with it, but not as much, so that the old plateau surfaces are tilted eastward. The east-flowing streams, gaining strength from steepening slopes and from increased water supply as the mountains rise high enough to become cloud barriers, rapidly deepen their canyons and extend themselves back into the range; Cimarron Creek nibbles away at the range until it cuts through and captures the waters of Moreno Valley. Meanwhile, the Canadian River, in response to repeated uplifts on the west, keeps shifting eastward and building new, successively lower flood plains on the soft Cretaceous shales; changing Quaternary climates, as Ice Ages come and go, may also cause shifts between downcutting and flood-plain building. The remnants of these abandoned flood plains make up the present Las Vegas Plateau.

During long wet spells in early Quaternary time, soft shale exposed in deep streamcuts at plateau fronts in central and southern Philmont becomes saturated and slides in scoop-shaped masses toward the plains, carrying chunks of sandstone or basalt with it, until 50 square miles is covered by hummocky landslides.

Beyond the flood plains and the landslides, varied rocks and structures have gradually been exposed by stripping off of the loose Tertiary gravel and are controlling the shapes of the land forms being sculptured, mainly by gravity and sheetflow. Steeply dipping dikes, sills, and hard sedimentary rocks become narrow ridges; alternate hard- and soft-layered sedimentary and volcanic rocks that have low dips become steepsided benchlands; intricately fractured metamorphic rocks in the range core are chopped into narrow canyons and ridges.

Today, the range is higher and more rugged than it has ever been. Even if the crust beneath stays quiet, the range will loom above the plains for many thousands of years. It will become ever more deeply sculptured, until the range crest itself is attacked; then it will gradually be worn lower and rounder. If the recent past is any guide, though, the earth beneath Philmont will remain restless and the range will continue to rise, and the bordering plains with it, creating even grander vistas for our remote descendants to wonder at and enjoy. It is probably rising at this moment . . . . .

INDIAN WRITINGS from canyon of North Ponil Creek. (Fig. 131)

EXIT WONDERING

Our four-dimensional tour of Philmont is over. We have seen and said much, but it still is only a beginning. If Philmont is well thought of as a cake, we have seen the layers and sampled the icing, but we could not begin to write the recipe. We have a fairly good idea of what happened in the last 300 million years on the surface and for a few miles beneath, and we have some broad hints about the billion years before that; but we have very little idea of why any of these things happened.

Take, for instance, a sand grain in Cimarron Creek. It is easy to decide that it is there because the water, flowing downhill under the pull of gravity, was able to pick it up from a weathered outcrop and move it; using a little imagination, we can even predict that the lofty Cimarron Range may finally be worn down to a monotonous plain by this process. But we have made few observations of exactly how debris is supplied to streams and other transporting agents, and how the erosion process really works; we have given little thought to the marvelous interplay of climate, rock type, structure, and time that control the nature and history of streams.

Why is the Cimarron Range there in the first place? To say that the mountains were tilted or folded or faulted up describes what happened but not why. Why do parts of the earth's crust rise against the pull of gravity? And, once risen, how can tall mountains like the Cimarron Range loom above the plains for many millions of years when the rate of erosion suggests that they should be leveled in a few million years? Some mountains must keep rising as they are eroded—why? On the other hand, all mountains do not rise indefinitely—if they did, the sedimentary cover would have long since been stripped from all of them, as it is beginning to be stripped from the Cimarron Range. Why do they stop rising?

And what of our sand grain and its neighbors, worn and washed off the mountains? How is it that sediments can become thousands of feet thick below a mere film of water on a river flood plain or in shallow waters no more than a few hundred feet deep on the ocean rim? Parts of the earth's crust must sink as sediments accumulate, just as neighboring parts rise—why? Why did Philmont stand a little above or a little below the sea for most of the several hundred million years of Paleozoic and Mesozoic time and then get caught up in a spasm of crumpling and faulting in its western part in early Tertiary time? Why did the rest of it not crumple too? And why, after the crumpling stopped, did the mountains, and plains too, rise thousands of feet almost straight up in later Tertiary and Quaternary time?

While we are asking embarrassing questions about earth movements, we might try to ask a few about the dacite porphyry and other igneous rocks that invaded the Philmont cake during the main time of folding. Perhaps these rocks were produced by folding sediments down so deeply and compressing them so much that they melted enough to flow. But if this is so, where are the Tertiary metamorphic rocks that should have formed at earlier stages in the same process? Still buried? Or are these igneous rocks brand new, from melts that have never been at the surface before? If this was their first trip through the metamorphic cycle, had they been liquid ever since the earth formed (and when was that?) or were they solid through most of geologic time until something happened (what?) to melt them and force them toward the surface in early Tertiary time? No matter how they formed, how did these sticky liquids make room for themselves, if they did not melt the solid rocks above? How did they get so different in their makeup and appearance, to end as dacite porphyry and andesite, basalt, and lamprophyre? And how do the gold and copper deposits fit into the story?

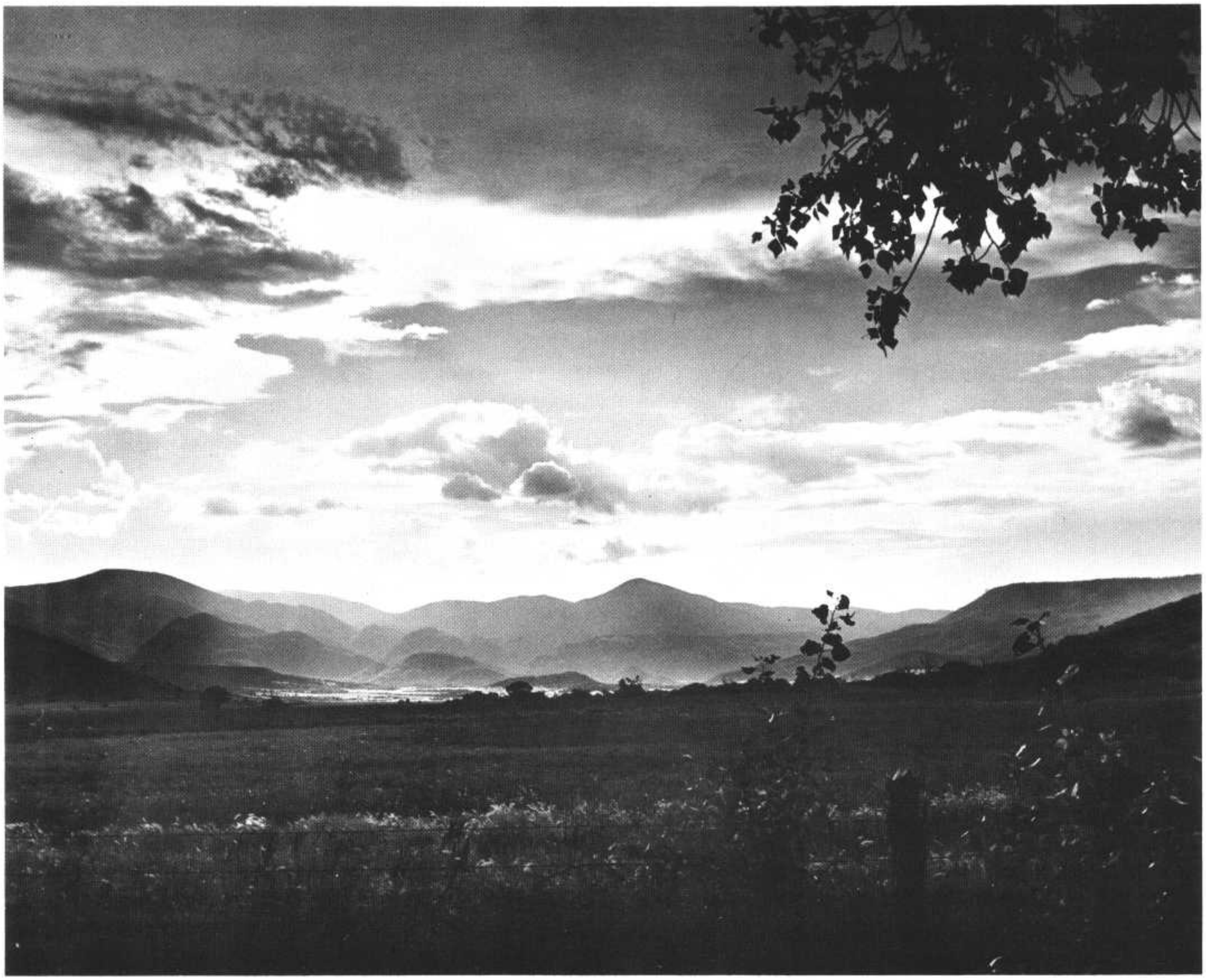
We have paid little attention to perhaps the most fascinating part of geology—the geology of living things. Why and how do new forms of plants and animals develop? Why do animals and plants become extinct? Do changes in surface conditions, such as retreats and advances of the sea or changes of climate, have anything to do with the rise and extinction of plant and animal species?

In this book we have not tried to answer any of these hard questions, although in the century and a half since geology came to be recognized as a science, convincing explanations have been carefully worked out for some of them and for many others that arise whenever a bit of the earth is looked at thoughtfully. A visit to the stacks of a large geological library gives an idea of what is known about geology and related sciences. Millions of books and articles about geological subjects have been printed, and thousands are added each year.

But there is so much more to learn! Only a few percent of the earth's land surface has been mapped even in the same crude detail as Philmont. The earth is nearly 8,000 miles across, but the deepest man has himself gone is less than 2 miles below sea level on land and less than 8 miles at sea. The deepest he has probed by drilling is less than 6 miles below sea level. He had explored only a tiny fraction of the sea and its floor, and the sea covers more than two-thirds of the earth's surface.

Man's personal sample of geologic time is even smaller than his sample of geologic space. His most ancient writing with the faintest geologic flavor—the drawings of animals made by Cro-Magnon man in the caves of southern France—take us back no more than 10,000 years, and continuing reliable records of geologic phenomena—such as sea and land levels, climate, streamflow—have been made only for a few decades and in a few places.

With so much of the earth unknown, it is not surprising that geologists have not reached agreement about all the processes going on near the surface or about some of the more difficult questions of deeper structure, earlier time, and fundamental causes. This is what keeps geology exciting as well as useful. If you want to go further into what geologists have done and thought, a world of stimulating and entertaining literature awaits you in practically any library. Books you might start with are listed on the next page.



THE SUN SETS behind the Cimarron Range. View from State Highway 21 near Scout Ranch Training Center. (Fig. 132)

SUGGESTED READING

General geology and geophysics

GEOLOGY, C. L. Cooper and others, New Brunswick, N.J., Boy Scouts of America, 1953. Merit badge series.

MODERN EARTH SCIENCE, by W. L. Ramsey and R. E. Burckley. New York, Holt, Rinehart, and Winston, 1961. 630 p. High school text.

EARTH SCIENCE, THE WORLD WE LIVE IN, by S. N. Namowitz. 2d ed. Princeton, N.J., Van Nostrand, 1960. 614 p. High school text.

DOWN TO EARTH: AN INTRODUCTION TO GEOLOGY, by C. G. Croneis and W. C. Krumbein. Chicago, University of Chicago Press, 1936. 499 p. Paperback; easy college text.

PHYSICAL GEOLOGY, by L. Don Leet and Sheldon Judson. 2d ed. New York, Prentice-Hall, 1958. 502 p. Detailed college text.

PRINCIPLES OF GEOLOGY, by James Gilluly, A. C. Waters, and A. O. Woodford. 2d ed. San Francisco, Freeman, 1959. 534 p. Detailed college text.

THE PLANET EARTH, by the Editors of "Scientific American." New York, Simon & Schuster, 1957. 176 p. Paperback; on the forces that stir the earth's crust, oceans, and atmosphere.

A PRIMER ON WATER, by L. B. Leopold and W. B. Langbein. Washington, U.S. Government Printing Office, 1960. Paperback.

Landscape and seascape geology

GEOMORPHOLOGY: AN INTRODUCTION TO THE STUDY OF LANDSCAPES, by A. K. Lobeck. New York, McGraw-Hill, 1939. 731 p. Splendidly illustrated college text.

THIS SCULPTURED EARTH: THE LANDSCAPE OF AMERICA, by J. A. Shimer. New York, Columbia University Press, 1959. 255 p. Non-technical account of the origins of our scenery.

GLACIAL AND PLEISTOCENE GEOLOGY, by R. F. Flint. New York, John Wiley & Sons, 1957. 553 p. College text.

MOUNTAINS, by L. J. Milne and Margery Milne. New York, Time, Inc., 1962. 192 p. (Life Nature Library.)

THE DESERT, by A. S. Leopold. New York, Time, Inc., 1961. 192 p. (Life Nature Library.)

THE EARTH BENEATH THE SEA, by F. P. Shepard. Baltimore, Johns Hopkins Press, 1959. 275 p.

THE SEA AROUND US, by Rachel L. Carson. New York, Oxford University Press, 1951. 230 p.

VOLCANOES; IN HISTORY, IN THEORY, IN ERUPTION, by F. M. Bullard. Austin, University of Texas Press, 1962. 441 p.

History of the earth and its life

BIOGRAPHY OF THE EARTH; ITS PAST, PRESENT, AND FUTURE, by George Gamow. Rev. ed. New York, Viking, 1959. 242 p. Paperback.

THE EVOLUTION OF LIFE, by F. H. T. Rhodes. Baltimore, Penguin Books, 1962. 304 p. Paperback.

THE FOSSIL BOOK; A RECORD OF PREHISTORIC LIFE, by C. L. Fenton and M. A. Fenton. Garden City, N.Y., Doubleday and Co., 1958. 482 p.

FOSSILS, by F. H. T. Rhodes and others. New York, Golden Press, 1962. Paperback.

FOSSILS; AN INTRODUCTION TO PREHISTORIC LIFE, by W. H. Matthews. New York, Barnes & Noble, 1962. 337 p. Paperback

LIFE OF THE PAST; AN INTRODUCTION TO PALEONTOLOGY, by G. G. Simpson. 2d ed. New Haven, Yale University Press, 1961. 198 p. Paperback. Easy college text.

DINOSAURS, THEIR DISCOVERY AND THEIR WORLD, by E. H. Colbert. New York, Dutton, 1961. 300 p.

MANKIND IN THE MAKING; THE STORY OF HUMAN EVOLUTION, by W. W. Howells. Garden City, N.Y., Doubleday, 1959. 382 p.

Rocks and minerals

ROCKS AND MINERALS, by H. S. Zim and Paul Shafer. New York, Golden Press, 1957. 160 p. Paperback. Many colored pictures.

THE ROCK BOOK, by C. L. Fenton. New York, Doubleday, 1940. 357 p. Well-illustrated general book.

GETTING ACQUAINTED WITH MINERALS, by G. L. English and D. E. Jensen. 2d ed. New York, McGraw-Hill Book Co., 1958. 362 p.

A FIELD GUIDE TO ROCKS AND MINERALS, by F. H. Pough. 3d ed. Boston, Houghton Mifflin, 1960. 349 p.

For further information

EARTH FOR THE LAYMAN, by M. W. Pangborn, Jr. Washington, American Geological Institute, 1957. 68 p. (AGI report 2, 2d ed.). $1.00. A list of nearly 1,400 good books and pamphlets of popular interest on geology, mining, oil, maps, and related subjects, arranged by subject or area, and provided with notes indicating interest level and contents.

You may also wish to write to your State Geological Survey or to the U.S. Geological Survey, Washington, D.C., 20242, for further information on your own State, and to the American Geological Institute, 1444 N St., N.W., Washington, D.C. 20005, for information on geological careers and education.

ABOUT THIS BOOK

This book is an outgrowth of a regional study of the mineral-fuel resources of the Sangre de Cristo Mountains, a project under the direction of C. B. Read. A. A. Wanek and Read had planned to write a popular account of Philmont geology themselves and had made a start by preparing a geologic reconnaissance map of the Philmont quadrangle in 1956–57. By late 1957, however, it had become clear that other obligations would prevent their writing the text.

Encouraged by R. Maurice Tripp, then chairman of the Boy Scout Committee of the American Association of Petroleum Geologists, G. D. Robinson volunteered to complete the project. The geologic map made by Wanek and Read and a brief technical file report on the area by Wanek were generously turned over to Robinson. The map and report constitute the factual base for much of this book; indeed, the book could not exist without them. In addition, Read and Wanek spent several days at Philmont with Robinson, providing an invaluable introduction to the area and its geologic problems.

Because the primary interest of Read and Wanek was in the fuel resources, their work emphasized the sedimentary rocks. Assisted by W. H. Hays and M. E. McCallum, Robinson spent the summer of 1958 at Philmont, refining and modifying their map in the areas of igneous and metamorphic rocks and collecting representative specimens of all rocks for laboratory study. Dan Hawkins also assisted briefly in 1958. Their stay at Philmont was facilitated by the generosity and cooperation of the Boy Scouts of America. Special mention must be made of the aid and encouragement of Ray H. Bryan, Assistant to the Chief Scout Executive, and of Jack L. Rhea, Director of Camping. Several residents of Cimarron, particularly J. W. Leitzell and William Brewster, supplied valuable aid and information, as did Mr. Richard Atmore, of Atmore Brothers Ranch, and Mrs. Doris L. Atmore, Postmaster at Ute Park.

During the summer, E. F. Patterson, Staff Photographer, joined the group for several days; and J. R. Stacy, Scientific Illustrator, accompanied them for several weeks. Patterson and Stacy each took photographs that were invaluable in preparing this volume; most of the photographs which illustrate it are theirs. In addition, Stacy made many on-the-scene sketches.

During the winter of 1958–59, Hays studied more than 200 thin sections, to provide the main basis for the descriptions of igneous and metamorphic rocks. McCallum spent several weeks at Philmont in 1959, further refining the geologic map of the flanks of Touch-Me-Not Mountain and of the northwest corner of Philmont.

Thus, essentially all the basic data for this book were in Robinson's hands by the fall of 1959. Owing to the press of other duties, however, the writing was not completed until the winter of 1962. During this part of the task, Alfred Clebsch, Jr., and S. W. Lohman assisted materially in the preparation of the sections on ground water. Concurrently, Stacy worked on the diagrams and sketches; assisted by E. P. Krier and Anthony Denson, he also prepared the final photographic copy. Credit for the individual photographs has been given in the list of illustrations.

The reading list in the preceding chapter was prepared with the help of Mark W. Pangborn, Jr., of the Geological Survey Library.

Peter W. Lenz, of Wheat Ridge, Colo., an Eagle Scout who recently spent a summer at Philmont, read the manuscript, and many members of the Geological Survey reviewed part or all of it. It has profited much from their suggestions.

Except for casual mention by naturalists attached to early armies of exploration and surveys of the West, Philmont was bypassed by geologists until the start of this century. Then, L. C. Graton briefly examined the gold deposits and prospects in the Baldy district and on Cimarroncito Creek. During and just after World

War I, W. T. Lee intensively studied the coal-bearing rocks in northern Philmont. He also examined the Aztec gold mine near Baldy. In 1941, J. F. Smith, Jr., and L. L. Ray made a geologic reconnaissance of the Cimarron Range, as a sequel to their study of Moreno Valley in 1939.

The main publications resulting from the previous work are:

Graton, L. C., 1905, Colfax County, *in* Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., The ore deposits of New Mexico: U.S. Geol. Survey Prof. Paper 68.

Lee, W. T., 1916, The Aztec gold mine, Baldy, New Mexico: U.S. Geol. Survey Bull. 620-N, p. 325-330.

Lee, W. T., and Knowlton, F. H., 1917, Geology and paleontology of the Raton Mesa and other regions in Colorado and New Mexico: U.S. Geol. Survey Prof. Paper 101, 450 p.

——— 1922, Description of the Raton, Brilliant, and Koehler quadrangles, New Mexico–Colorado: U.S. Geol. Survey Geol. Atlas, Folio 214, 17 p., 2 sheets, illustrations, 10 maps.

——— 1924, Building of the southern Rocky Mountains: Geol. Soc. America Bull., v. 34, no. 2, p. 285-300.

Ray, L. L., and Smith, J. F., Jr., 1941, Geology of the Moreno Valley, New Mexico: Geol. Soc. America Bull., v. 52, no. 2, p. 177-210.

Smith, J. F., Jr., and Ray, L. L., 1943, Geology of the Cimarron Range, New Mexico: Geol. Soc. America Bull., v. 54, no. 7, p. 891-924.

To make this book more palatable to the casual reader, the trappings of scholarship that customarily adorn more technical writings have been omitted. The main omission has been of references. Yet it must be plain that this book, far more than most technical reports, depends on the work and thoughts of others; to far more than the customary degree, the local information presented, and its interpretation, had to be borrowed from the colleagues and predecessors named above. A search of their cited works will reveal the extent of indebtedness—as well as occasional differences of opinion. For another thing, this volume offers a host of general geologic concepts, and many examples from beyond Philmont, that could not possibly arise from any writer's direct experience. They are part of the common property of geology; they normally would not be documented in technical reports and are not further supported here. It seems appropriate, however, to document certain borrowed observations and ideas that are neither common property nor published in the works already listed. Their sources are listed below, in their order of appearance in the text.

Scattered statements about human history, such as Coronado's march and the founding of Cimarron

Federal Writer's Project, 1953, New Mexico: Hastings House, New York.

Production of gold, iron and gravel

U.S. Bureau of Mines, 1960, Mineral facts and problems: Bull. 585.

Resemblance of Halymenites to filled crab burrows

Weimer, R. J., and Hoyt, J. H., 1961, *Callianassa major* burrows, geologic indicators of littoral and shallow neritic environments: Geol. Soc. America Spec. Paper 68, p. 321.

Rank and quality of Philmont coal

Lee, W. T., 1924, Coal resources of the Raton coal field, Colfax County, New Mexico: U.S. Geol. Survey Bull. 752, 254 p.

Age of Precambrian rocks in Colorado Front Range

Aldrich, L. T., and others, 1958, Radioactive ages of micas from granitic rocks by Rb-Sr and K-A methods: Am. Geophys. Union Trans., v. 39, no. 6, p. 1130.

Phair, George, and Gottfried, David, 1958, Laboratory data on the age of the Precambrian batholithic rocks and skarn deposits of the Colorado Front Range [abs.]: Geol. Soc. America Bull., v. 69, no. 12, pt. 2, p. 1739.

Giffen, C. E., and Kulp, J. L., 1960, Potassium-Argon ages in the Precambrian basement of Colorado: Geol. Soc. America Bull., v. 71, p. 219-222.

Radioactivity dates in table on page 93

Holmes, Arthur, 1960, A revised geological time scale: Edinburgh [Scotland] Geological Society, v. 17, pt. 3, p. 183-216.

Faul, Henry, 1961, Geologic time scale: Geol. Soc. America Bull., v. 71, p. 637-644.

Thick Tertiary gravels north of Philmont

Johnson, R. B., 1961, Coal resources of the Trinidad coal field in Huerfano and Las Animas Counties, Colorado: U.S. Geol. Survey Bull. 1112-E, 180 p.

Pre-Pennsylvanian strata in surrounding regions

G. H. Dixon, oral communication, 1962.

W. W. Mallory, oral communication, 1962.

G. H. Bachman, oral communication, 1962.

Measuring dip and strike

Gilluly, James, Waters, A. C., and Woodford, A. O., 1959, Principles of geology: 2d ed., San Francisco, Freeman, p. 91-92.

Possible underthrust origin of the Precambrian core of the Cimarron Range

C. B. Read, oral communication, 1958.

The Elm landslide

Gilluly, James, Waters, A. C., and Woodford, A. O., 1959, Principles of geology: 2d ed., San Francisco, Freeman, p. 178-179.